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Factors Influencing Accelerometer Measurement Capabilities -
A Practical Measurement Guid^

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20034

FACTORS INFLUENCING ACCELEROMETER MEASUREMENT CAPABILITIES - A PRACTICAL MEASUREMENT GUIDE

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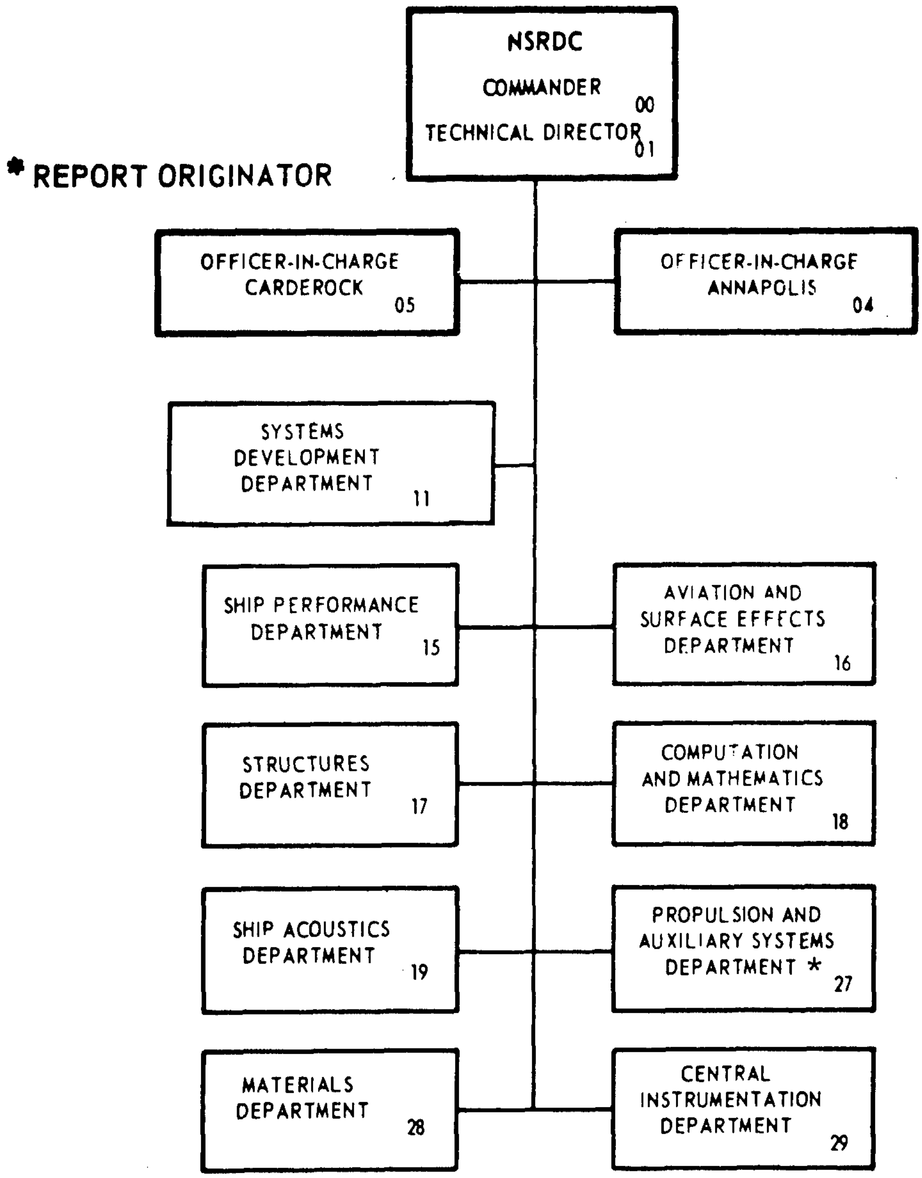

ABSTRACT

After a brief review of the electromechanical functioning of the piezoelectric accelerometer, factors affecting its dynamic response characteristics and therefore the validity of vibration measurement are discussed. Consideration is given to variables such as shunt resistance and capacitance, mounting methods, base bending, cable noise, ground-loop currents, and environmental effects. Approved accelerometer mounting techniques that will ensure the accuracy and repeatability of the measurement are also described.

ADMINISTRATIVE INFORMATION

This work was authorized by NAVSHIPS under Task Area SF 35 452 001, Task 01350, Work Unit 1-2742-101.

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INTRODUCTION

The piezoelectric accelerometers play a vital part in detecting, measuring, and identifying structureborne noise. Accelerometers used for this purpose are carefully selected on the basis of reliability and their dynamic performance characteristics. Prior to use, the transducer is dynamically calibrated under a prescribed set of conditions to determine its reference sensitivity. Under actual field use, however, the transducer may be unknowingly subjected to a different set of conditions or a different measurement environment. As a consequence, the normal dynamic response of the accelerometer is altered and an unknown amount of error is injected into the noise measurement. To ensure the accuracy and validity of structureborne-noise measurements made with piezoelectric accelerometers, some of the variables known to affect the data integrity are discussed in this report.

THE PIEZOELECTRIC ACCELERATION TRANSDUCER

In the broadest sense, a transducer is a device that converts energy from one form to another. An acceleration transducer is a device that converts complex vibratory motion into an electrical signal which is proportional to the acceleration. The piezoelectric accelerometer utilizes a piezoelectric material as the transduction element. The word piezo is derived from the Greek "Piezein" meaning to squeeze or press. One of the basic functions of the piezoelectric* element is to act as an electrical generator, when rapidly varying pressure is applied. The earliest materials used for this purpose were all "natural" or single crystal materials such as Rochelle salt and quartz. For many years the practical use of piezoelectricity was restricted by the difficulties inherent in matching fixed properties of the natural crystals with the requirements of the device.

In the early 1940's it was discovered that piezoelectricity could be induced artificially in some polycrystalline ceramic materials. As a result, today's piezoelectric device may have a transduction element of crystalline ceramic such as barium titanate, lead zirconate, or lead titanate, and lead metaniobate. The importance of these materials lies in the fact that the piezoelectric properties of ceramic materials can be controlled in the manufacturing process. Thus, important properties such as the dielectric constant (which determines the internal capacity) and the coupling coefficient (which is a measure of the efficiency in converting energy from one form to another) can be tailored to meet the requirements of the device.

BASIC ACCELEROMETER DESIGN AND OPERATION

A unique characteristic of the piezoelectric accelerometer is its ability to reproduce complex vibratory motion at frequencies ranging from approximately 5 to 10,000 Hz** and above. Its dynamic performance characteristics over this frequency range are controlled largely by the choice of piezoelectric material and the mechanical design. The low-frequency response of the accelerometer is determined primarily by the RC time constant of the piezoelectric sensor and the input resistance of the matching electronics. The high-frequency response of the transducer is a function of its mechanical characteristics. Since a discussion of transducer error requires an understanding of the functions of both the electrical and mechanical portions of the system, simplified diagrams of the piezoelectric accelerometer and its equivalent charge and voltage circuits appear as figures 1 and 2.

*The Curie brothers, Paul and Pierre, are credited with having discovered piezoelectricity in 1880.
**Abbreviations used in this text are from the GPO Style Manual, 1973, unless otherwise noted.

THE SPRING-MASS SYSTEM

The acceleration transducer is usually depicted as a spring-mass system as shown in item (a) of figure 1. The mass (M) is tied to the transducer case through a spring of stiffness (K) and a damping coefficient (C). The piezoelectric element functions as the spring element of the seismic system. For this reason, the overall transducer response, including resonant frequency, will be affected by the element stiffness. When an acceleration is applied to the base of the transducer, the mass moves relative to the base. One of the simplest accelerometer designs is the "compression" design shown in item (b) of figure 1. It consists of a piezoelectric crystal, one side of which is connected to an inertial mass. The other face of the crystal is fastened to the accelerometer base which is attached to the place where the vibratory motion is to be measured. With upward motion of the base, the inertia of the mass causes it to have a downward force, compressing the crystal wafer, and generating a voltage across it. On downward acceleration, the upward force on the mass generates a voltage of the opposite polarity. The electrical signal produced is proportional to the force exerted on the crystal by the mass. In accordance with Newton's second law represented by F=Ma, the force on the sensing element created by the acceleration equals the mass times the acceleration. Varied types of designs are available in commercial piezoelectric accelerometers. The center post-mounted compression type shown in item (c) of figure 1 is favored for many applications because of its relatively high acceleration sensitivity and the high degree of isolation (from extraneous effects) provided by the center post design.

THE PIEZOELECTRIC CIRCUIT

The circuits illustrated in figure 2 concern the piezoelectric generator only. In item (a), figure 2, the piezoelectric sensor is shown to have an internal resistance, capacitance, and inductance. In use the effects due to the internal inductance are far beyond the upper frequency range of the transducer and thus can be ignored. In the majority of applications, the internal resistance (which normally exceeds 20,000 megohms) can also be ignored since it is much larger than the shunt or input resistance of the matching electronics used in the system. The effect of the shunt resistance and capacitance at low test frequencies will be discussed later. The piezoelectric sensor is effectively a capacitor which produces a charge (q) across its plates, proportional to a force applied to the crystal. Thus, the transducer can be represented as a charge generator as shown in item (b) of figure 2. When the transducer is considered as a charge generator, the charge (q) is equal to the product of the open-circuit voltage and the crystal capacity, $q = eC_p$. The piezoelectric sensor can also be represented as a voltage generator and a series capacitance as shown in item (c) of figure 2. The open-circuit voltage (e) out of the transducer is equal to the generated charge divided by the transducer capacity, $e = q/C_p$.

THE ACCELEROMETER-AMPLIFIER SYSTEM

Thus far we have considered only what happens inside the accelerometer. For practical measurements a cable and amplifier electronics must be added to the accelerometer. The electrical output from the crystal accelerometer is almost always in the mV range and thus too low to be used directly with meter units requiring mW of power for deflection. Consequently, the accelerometer must be used with some form of electronic amplifier that can deliver power. There are two types of signal-conditioning devices generally used for this purpose; the voltage and the charge amplifiers. The charge amplifier is sometimes referred to as a "charge converter" since it converts charge, generated by the accelerometer, into a voltage that can be measured. The selection of an amplifier to be used as instrumentation for measuring vibration is determined by the specific requirements of the system. Both voltage and charge amplifiers offer certain advantages depending upon the parameters involved. Simplified diagrams of the two types of signal-conditioning devices are shown in figure 3 along with the accelerometer and its cable.

CAPACITANCE LOADING EFFECTS

In the accelerometer voltage amplifier system it is important that we consider the total capacitance, ie., accelerometer, cable, and input capacitance of the first electronic unit in the readout system. It was shown earlier that the open-circuit voltage (e) out of the transducer is equal to the charge sensitivity (Q) divided by the internal transducer capacitance C_p, $e = Q/C_p$. From figure 3, it can be seen that both the cable capacitance (C_c) and the input capacitance (C_a) of the amplifier shunt the internal capacity (C_p) and thus act to reduce the open-circuit voltage sensitivity of the transducer.

$$E_{\text{new sensitivity}} = \frac{Q}{C_p + C_c + C_a}.$$

The effect of the cable and amplifier shunt capacitance on accelerometer open-circuit sensitivity can be shown by use of the following typical circuit values.

e = open-circuit voltage sensitivity (60 mV_{peak}/g_{peak}).

Q = charge sensitivity (60 pC_{peak}/g_{peak}).

C_p = crystal capacity (1000 pF*).

C_c = cable capacity (100 pF) (approximately 3 ft in length).

C_a = amplifier input capacity (10 pF).

E = new voltage sensitivity (shunted).

Computing open-circuit sensitivity

$$e = \frac{Q}{C_p} = \frac{60\,pC_{peak}/g_{peak}}{1000\text{ pF}} = \frac{60 \times 10^{-12}}{1000 \times 10^{-12}} = 0.060. \qquad (1)$$

$$e = 60.0\ mV_{peak}/g_{peak}$$

Computing effect of capacitance load on open-circuit voltage sensitivity

$$E_{\text{new sensitivity}} = \frac{Q}{C_p + C_c + C_a} = \frac{60\,pC_{peak}/g_{peak}}{1000 + 100 + 10} = \qquad (2)$$

$$\frac{60 \times 10^{-12}}{1110 \times 10^{-12}} = 54.0\ mV_{peak}/g_{peak}.$$

*The prefix pico refers to 10^{-12} and replaces the term micro-micro.

The capacitance load of 110 pF (cable + amplifier input) reduced the open-circuit voltage sensitivity by approximately 10% or about 1 decibel. With an interconnecting cable 10 feet in length (300 pF) the sensitivity would be reduced by approximately 17% or about 2 decibels. Since the apparent voltage sensitivity is related to the external shunting capacitance, correction factors must be applied whenever the system capacity during field use differs from that used in the original calibration of the transducer. The shift in the transducers' basic voltage sensitivity caused by using a different length of cable is easily computed by use of equation (2) above. The values for the charge sensitivity (Q), the crystal capacity (Cp) and the external shunt capacitance used in calibrating the transducer are usually given with the calibration data supplied by the manufacturer. The reduction of open-circuit voltage due to shunt capacitance is shown graphically in figure 4.

In the charge amplifier system, figure 3, the input voltage is relatively unimportant. The output voltage which results from a change in signal input is returned to the input circuit through the feedback capacitor (C_f), in the direction to maintain the input circuit voltage at or near zero. The net charge input is stored in the feedback capacitor, producing a potential difference across it equal to the value of charge divided by the value of capacitance. Since the charge amplifier senses charge rather than voltage, changes in the length of interconnecting cable cause no shift in the calibrated charge sensitivity of the accelerometer. The charge amplifier, however, is not without certain shortcomings. It is sensitive to spurious noise generated within the input cable and its noise level is found to increase appreciably as input cable length is increased. This effect of cable length on signal quality may prohibit the use of the charge system for applications where long input cables are needed for the acquisition of extremely low-level vibration data.

EFFECT OF INPUT SHUNT RESISTANCE ON LOW FREQUENCY RESPONSE

It has been shown how the external shunt capacitance affects the basic voltage sensitivity of the piezoelectric accelerometer. Of equal importance is the shunting input resistance of the electronic instrument to which the accelerometer is connected. With a voltage amplifier, the low-frequency response of the accelerometer is affected by the time constant (T) of the combined RC circuit where (R) is the amplifier input resistance and (C) is the sum of the accelerometer, amplifier input, and cable capacitances. The influence of the time constant on the low-frequency response can be shown by use of the low-frequency response versus loading curve of figure 5 and by the typical values of capacitance and resistance given below under example A.

Example A

Tranducer crystal capacity. . . . . .135 pF

Interconnecting cable capacity. . . . . . .290 pF

Amplifier input capacity. . . . . 10 pF

Amplifier input shunting resistance. . . .10 megohms

The time constant (T) of the accelerometer-cable-instrument combination given in example A is equal to the product of shunting resistance (R) times the shunting capacitance (C); that is, T = RC. Therefore, in our example

$$RC = 10 \times 10^{6} \times (135 \times 10^{-12} + 290 \times 10^{-12} + 10 \times 10^{-12}) = 0.00435 \text{ second.}$$

From the response curve of figure 5, we see that the abscissa is the factor FRC, frequency times RC, the time constant. The relative response of the transducer (for a given FRC factor) is shown in the left hand ordinate of the graph. Using the time constant from example A and the FRC from the loading curve, the low-frequency response of the accelerometer-cable-instrument combination can be calculated to determine the frequencies at which the response voltage is reduced by any given percent. To determine the frequency at which the response voltage is reduced by 10% we refer to figure 5 to find that FRC = 0.3 for 90% response. Thus,

$$\text{Frequency} = \frac{0.3}{RC} = \frac{0.3}{0.004350} = 69 \text{ Hz.}$$

To determine the frequency at which the response voltage is reduced by 20% (approximately 2 dB) FRC = 0.2 for 80% response

$$\text{Frequency} = \frac{0.2}{RC} = \frac{0.2}{0.004350} = 46 \text{ Hz.}$$

The frequency at which the response is reduced by 30% (approximately 3 dB) FRC = 0.145 for 70% response

$$\text{Frequency} = \frac{0.145}{RC} = \frac{0.145}{0.004350} = 33 \text{ Hz.}$$

To further illustrate the influence of the RC constant on the transducer's low-frequency response, low-frequency roll-off was also calculated for an amplifier input resistance of 100 megohms. The effect of the two different shunt resistance values on low-frequency response is shown graphically in figure 6.

It is evident that increasing the value of the input shunt resistance improves the low-frequency response of the accelerometer. The low-frequency response can also be improved by the use of additional shunt capacitance, such as long cables, to increase the RC time constant. This technique, however, has the disadvantage of reducing the voltage sensitivity, as discussed earlier, under capacitance loading effects. Another way to extend the response is to use an intermediate amplifier (cathode follower) with a higher input resistance. A typical unit has an input resistance of 10^9 ohms. In any application where extended low-frequency measurements are required, the response of the coupling amplifier must also be determined since the amplifier may cause a greater drop in low-frequency response than that caused by the RC constant of the system.

From the foregoing it can be seen that to maintain accuracy in extended low-frequency measurements, it is essential that we establish the low-frequency roll-off characteristics of the accelerometer-cable-instrument combination. Good housekeeping should also be observed, making certain that cable connectors and receptacles are dry and free of any contaminant (such as skin oils, moisture, or dirt) that may alter the low-frequency response. When the transducer is exposed to a humid environment, it may also be advisable to seal the cable connector to prevent moisture from entering the assembly and altering the RC constant of the system. In vibration applications where a voltage system is to be used, it is good practice to perform laboratory sensitivity and frequency response calibrations on the accelerometer with the particular cable and amplifier to be used in making the field measurement. Because alteration of the RC constant does represent a potential source of error in the accelerometer voltage system, many users prefer charge amplifiers to voltage amplifiers when making extended low-frequency measurements. When used with a charge amplifier, the low-frequency response limit is usually only that of the charge amplifier circuitry. This is usually about 2 to 5 Hz or lower.

While on the subject of signal-conditioning devices and their effect on accelerometer response, consideration must also be given to a relatively new signal-conditioning technique. This technique utilizes transistorized circuitry to convert the high capacitive impedance of the piezoelectric accelerometer crystal to a low output impedance of less than 150 ohms. With today's miniaturization capabilities it is possible to combine the piezoelectric seismic system and solid state amplifier into one case. This type of accelerometer is generally referred to as an integrated-accelerometer or integrated-amplifier. The solid state impedance converter circuitry may also be used with the convential piezoelectric accelerometer by installing the unit in the coaxial cable. When used external to the accelerometer, the impedance converter unit is usually referred to as an in line amplifier or line driver. The impedance converter device may be designed to operate as either a charge or voltage converter. The one significant advantage of the integrated-circuit technique is that it changes the open-circuit voltage sensitivity of the accelerometer into a useful low impedance signal. While this results in some improvement in the signal-to-noise ratio of the system, it represents no significant improvement over the capabilities of the convential charge amplifier system.[1] One major shortcoming of the integral device is its limited temperature range. In most designs the transistorized circuitry is limited to an upper temperature range of approximately 200° F. In short, the integral device cannot be considered a replacement for standard accelerometers and signal conditioning devices but rather a supplement that will fulfill specific vibration measurement needs.

FACTORS CONTRIBUTING TO ERROR IN THE HIGH-TEMPERATURE VIBRATION MEASUREMENT

The majority of piezoelectric vibration-sensing materials used in high-temperature transducers are known to exhibit some variation in their response characteristics when exposed to elevated temperatures. A deviation of 30% in acceleration sensitivity is not uncommon when temperatures approaching the upper limit of the transducers rated temperature range are encountered.[2] In addition, flash temperatures may create high thermal stresses in the transducer housing. The resulting voltage output, indirectly created by differential expansion of the housing materials, produces false and undesirable transients in the vibration measurement. Knowledge of these phenomena and their effects on transducer response is essential in order to minimize error in high-temperature data.

ACCELEROMETER MAXIMUM RATED TEMPERATURE RANGE

The usefulness of any piezoelectric material for high-temperature applications depends on the characteristic temperature of the material, called the Curie temperature. The Curie temperature, is that temperature at which a crystalline change takes place in the piezoelectric material. When this happens, the ceramic element of the transducer suffers permanent and complete loss of piezoelectric activity. Thus, for any piezoelectric accelerometer the Curie temperature is the absolute maximum temperature. In practice, the operating temperature must be limited to some value substantially below the Curie temperature of the material. For example, if the Curie temperature of the piezoelectric material is 600° F, the usable upper limit may be given as 450° F. Thus, to avoid error in vibration measurements taken in a high-temperature environment, it is important that we select an accelerometer that has a maximum rated temperature equal to, or higher than, the temperature to which it will be exposed. Exposure to excess temperature for only a short period of time may cause a permanent reduction in the transducer's sensivitity. If undetected, the reduction in sensitivity will inevitably result in incorrect data.

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[1] Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

INFLUENCE OF HIGH-TEMPERATURE ON ACCELEROMETER ELECTRICAL CHARACTERISTICS

In addition, exposure to elevated temperatures below the Curie temperature alters both the piezoelectric and dielectric constants of the accelerometer crystal. As a consequence, the charge output, electrical capacity, and leakage resistance may vary significantly as a function of temperature. When used as a voltage generator, the accelerometer voltage sensitivity will vary with the ratio of charge sensitivity to the capacity. The effect of temperature on the charge, voltage, and crystal capacity of two high-temperature (500° F) accelerometers is shown in figures 7 and 8. The effect of temperature on the leakage resistance of two crystal materials is shown in figure 9.

INFLUENCE OF HIGH-TEMPERATURE ON ACCELEROMETER LOW-FREQUENCY RESPONSE

Measurement of the accelerometers electrical properties at elevated temperatures shows an increase in the electrical capacitance and a loss in the electrical leakage resistance of the crystal. The change in the internal capacity and resistance of the accelerometer due to temperature, affects the voltage sensitivity and low-frequency response in a manner similar to that described earlier when alterations were made in the external capacitance and shunt-resistance values of the system. Increasing the electrical capacitance lowers the transducers voltage sensitivity. Lowering the leakage-resistance value alters the transducers RC time constant and may alter the low-frequency response. Normally, the internal electrical resistance of the accelerometer crystal is extremely high (20,000 megohms or more) and its effects can be neglected. In high-temperature applications, however, it is not uncommon for the internal (shunt) resistance value of some piezoelectric materials to be reduced to 5000 megohms. Whether this reduction in resistance would result in degradation of the accelerometer low-frequency response would depend on the input impedance of the matching amplifier. Degradation of low-frequency occurs only in those instances where the accelerometer resistance value drops below that of the matching amplifier. Thus, low-frequency deviation would still be insignificant in those cases where the input impedance of the amplifier is in the order of 500 megohms. When temperature degradation of the low-frequency response is suspected, the use of a charge amplifier may be advisable to ensure valid low-frequency measurements.

COMPUTING CAPACITANCE LOADING EFFECT AT ELEVATED TEMPERATURES

The increase in the capacity of the accelerometer crystal as a function of temperature is of particular significance where the accelerometer is being used as a voltage generator. As noted earlier, when terminated in a voltage amplifier the voltage output is a known function of the ratio of internal (crystal) capacity to the external (cable and amplifier) shunt capacity. At room temperatures, where the charge output and crystal capacity of the accelerometer remain relatively stable, the effect of external capacitance loading on the open-circuit voltage sensitivity may be determined by the equation, $E = Q/\text{total capacitance}$. In computing the effect of capacitance loading on voltage sensitivity at elevated temperatures, however, the deviation in charge output and crystal capacity (with temperature increase) must be taken into consideration to avoid error in the computation and ensuing data. Needless to say, the accuracy of the computation depends primarily upon the precision of the techniques used to determine the accelerometer charge output, crystal capacity and temperature during the high-temperature calibration of the instrument.[3] Typical high-temperature accelerometer response data obtained from the calibration appears in figures 10 and 11. Knowing the relationship of charge sensitivity and crystal capacitance as a function of temperature makes accurate computation of the deviation of accelerometer sensitivity possible for any temperature and shunt capacitance load. For example, a typical high-temperature type accelerometer has a crystal capacity of 1095 pF, figure 10, and a charge sensitivity of 61 pC_{peak}/g_{peak}, figure 11, at a temperature of 80° F. The voltage sensitivity of this accelerometer is found to be 52 mV_{peak}/g_{peak} when its output is shunted by a 100 pF cable.

$$(80°\ F)\ldots\ \text{Voltage Sensitivity} = \frac{\text{Charge Sensitivity}}{\text{Total Capacity}} = \frac{61}{1095 + 100} = 52\ mV_{peak}/g_{peak}.$$

When the capacity and charge values obtained from the high-temperature calibration, figures 10 and 11 are used, the voltage sensitivity of the accelerometer, at a temperature of 450° F, is computed to be 37.5 mV_{peak}/g_{peak} when its output is shunted by a 100 pF cable,

$$(450°\ F)\ldots\ \text{Voltage Sensitivity} = \frac{\text{Charge Sensitivity}}{\text{Total Capacity}} = \frac{65.5}{1650 + 100} = 37.5\ mV_{peak}/g_{peak}.$$

In a similar manner, accelerometer voltage sensitivity at any given temperature may be computed to determine the effect of the shunt load on the response. For example, the sensitivity at 450° F is found to be 33.6 mV_{peak}/g_{peak} when the shunt load is increased to 300 picofarad.

$$(450°\ F)\ldots\ \text{Voltage Sensitivity} = \frac{\text{Charge Sensitivity}}{\text{Total Capacity}} = \frac{65.5}{1650 + 300} = 33.6\ mV_{peak}/g_{peak}.$$

In some applications it is found advantageous to reduce the voltage sensitivity of the accelerometer by increasing the shunt capacity. In high-temperature applications the value of capacity required to reduce the signal to the desired level may be computed by the following equation:

$$C_t = \frac{1000\ Q}{E} - C_p$$

C_t = total capacitance external to accelerometer, for which E is being established.

E = desired voltage level

Q = charge sensitivity at temperature of interest

C_p = accelerometer crystal capacitance at temperature of interest.

The use of this equation in high-temperature applications again emphasizes the need for observing the deviation in accelerometer capacitance and charge output with temperature in order to minimize error in the measurement.

Increasing the shunt capacity not only lowers the basic voltage sensitivity of the accelerometer but also alters the slope of the voltage-temperature response curve. The curves presented in figure 12 illustrate how the slope of the voltage-temperature response curve of the accelerometer may be altered by changing the shunt capacity load. The accelerometer manufacturer usually adjusts the ratio of internal (crystal) to external (cable) capacity to keep the voltage-temperature response within some specified tolerance. Thus, when the shunt capacity to be used in different from that used in the original temperature calibration, it may be advisable to compute the effect of the new shunt capacity on the slope of the voltage-temperature response curve.

In a similar manner, a series external capacity may be added to flatten the charge-temperature characteristic of the accelerometer. The series swamping equivalent circuit is shown in figure 13. In the use of the series swamping circuit, care must be taken to ensure that the value and location of the series capacitor is such that it will provide the desired compensation. The optimum value for the series capacitor is arrived at by subtracting the capacitance of the coaxial cable, $C_{ext\ 1}$, from that of the accelerometer.

$$C_{series} = C_p - C_{ext\ 1} = 1095\text{–}300 = 795\ \text{pF.}$$

The charge which appears at the charge amplifier can be expressed as:

$$Q_{amp} = Q\frac{C_{series}}{C_p + C_{ext\ 1} + C_{series}}$$

Q = basic charge sensitivity, pC/g

C_p = accelerometer capacity, pF

$C_{ext\ 1}$ = external capacity between the accelerometer and series capacitor

C_{series} = series swamping capacitor, pF

$C_{ext\ 2}$ = external capacity beyond the series capacitor has no effect when charge amplifier is used.

From the above equation it can be seen that the amount of charge appearing at the amplifier is affected by the capacitv of the cable between the accelerometer and the series capacitor. As the value of $C_{ext\ 1}$ increases, not only does the optimum value for C_{series} decrease, but the amount of charge appearing at the amplifier also decreases. If the compensating series capacitor is located within the charge amplifier, the loss in available charge is maximized and we now have a charge amplifier whose gain varies as a function of the source parallel capacity which includes the accelerometer and cable capacitance.

The foregoing examples point out the importance of selecting a high-temperature accelerometer compatible with the signal-conditioning electronics being used. The deviation of accelerometer charge output with temperature is usually different from the voltage output deviation as shown by the response curves of figures 7 and 8. To reduce the need for temperature compensation and also the amount of correction required in the vibration data, it is desirable, when using a charge amplifier, to select an accelerometer with flat charge characteristics. Conversely, when using voltage measuring electronics, it is important to select an accelerometer having flat voltage response characteristics. To assist the vibration engineer in selecting the type and model of accelerometer best suited for a particular application, most manufacturers supply data sheets listing the most important mechanical and electrical characteristics of the accelerometer. The tabulation below lists the accelerometer characteristics usually supplied by the manufacturer.

Piezoelectric Accelerometer Characteristics

Electrical and Dynamic	Mechanical
Charge Sensitivity	Crystal Operating Mode
Voltage Sensitivity	Material
Transducer Capacitance	Dimensions
Frequency Response	Weight
Mounted Resonance Frequency	Mounting Thread
Cross Axis Sensitivity	Cable, length, model
Strain Sensitivity	
Acoustic Sensitivity	**Environmental**
Magnetic Sensitivity	Temperature Range
Output Resistance	Humidity
	Salt Spray

TRANSIENT THERMAL EFFECTS

Some piezoelectric accelerometers exhibit an electrical output that is a function of rate of change of temperature. There are several pyroelectric effects that may cause the accelerometer to produce an electrical output. The usual pyroelectric output signal that occurs as a result of a slow variation in ambient temperature, is generally too low in frequency to be detected by the amplifier. If the amplifier low-frequency cutoff is below 1 Hz, however, measurement errors may be produced by this type of pyroelectric output. Of more significance perhaps is the spurious pyroelectric output caused by flash temperatures that produce a temperature gradient within the accelerometer housing. The resulting stresses, in turn, may be transmitted to the crystal element and produce an electrical output. This type of pyroelectric output is often high enough in frequency to be detected by the amplifier and may be sufficiently large to overload the amplifier, thus, making it inoperative during the time the pyroelectric output is present. Charge amplifiers as well as voltage amplifiers are found to respond to the transients that occur as a function of rate of change of temperature. It is also found that the magnitude of the pyroelectric output signal increases with temperature. Thus, where low level acceleration measurements are being made in a high-temperature environment, the spurious output due to thermal transients may easily obscure or mask the vibration data. The problem of spurious signals introduced by thermal transients can usually be avoided by one or more of the following methods:

- Select an accelerometer, such as the shear design, that is relatively insensitive to thermal transients.

- Use a suitable thermal shield around the accelerometer to exclude air currents and spurious output caused by flash temperatures.

- Use suitable low-frequency filters, where practical, to eliminate spurious signals.

ACCELEROMETER UPPER FREQUENCY LIMITATIONS

REFERENCE SENSITIVITY

The reference sensitivity of an accelerometer, expressed as either voltage or charge per unit of acceleration, is determined under a prescribed set of conditions including frequency, load impedance, amplitude, and mounting. Other errors are then referred to this value of sensitivity (hence the term "reference sensitivity"). In the calibration process, the accelerometer is rigidly stud-mounted to a vibration exciter and subjected to a measured vibration at various frequencies to determine its sensitivity deviation with frequency. The typical accelerometer has approximately flat sensitivity over a band of frequencies ranging from a few to thousands of hertz. The "flat" frequency range of the accelerometer is generally taken as that region in which the sensitivity does not change significantly (namely 4%) from the value found at 100 hertz. For the typical response curve shown in figure 14, the "flat" range extends from 10 to 5000 hertz. Vibration data obtained in this "flat" range will require no correction factors. At frequencies above the "flat" range, the spring-mass resonance of the accelerometer (which occurs at a much higher frequency) results in an increased electrical output for a given mechanical input. This increase in sensitivity continues until the resonance frequency of the accelerometer is reached. (The American National Standards Institute defines the resonance frequency as the frequency at which the sensitivity of the pickup is a maximum.)

To obtain accurate data at frequencies above the "flat" range, appropriate correction factors must be applied to compensate for the increase in accelerometer sensitivity. The correction factors required for high-frequency data are obtained by using absolute calibration methods to determine the sensitivity deviation of the accelerometer over the frequency range of interest. At the present time, high-frequency absolute calibration of accelerometers is limited to an upper frequency of approximately 10,000 hertz. Above this frequency the error in calibration increases rapidly. As a general rule, the upper frequency limit of an accelerometer is usually considered to be one-third of its mounted resonance frequency, for less than 1 dB error, assuming that the accelerometer is properly coupled to the equipment under investigation.

EFFECT OF MOUNTING ON ACCELEROMETER UPPER FREQUENCY RESPONSE

The upper frequency response of the accelerometer is generally considered to be a function of its mechanical characteristics. For example, an accelerometer having a stiff spring (crystal) and/or light mass will exhibit a high natural frequency. Conversely, a heavy mass and/or soft spring will have a low natural frequency. Thus, it would appear that by using known values for crystal spring constants and inertial mass, the resonance frequency of the accelerometer might be computed by use of the following equation:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}}$$

Unfortunately, the calculated resonance or theoretical limit of applicability is seldom the same as that found in practical applications. In practical applications, the accelerometer must be rigidly coupled to the structure undergoing investigation. As a consequence, the response characteristics of the accelerometer are affected and its usable upper frequency limited by interactions between the accelerometer and the structure.

STANDARD STUD MOUNTING

The resonance frequency shown in the response curve of figure 14, is referred to as the "mounted resonance frequency" and is obtained with the accelerometer rigidly stud mounted to the vibration calibrator. When stud mounted, the entire base of the accelerometer is in good contact with the surface of the calibrator. Under this condition, the best possible response is obtained from the accelerometer. Even with standard stud mounting, certain precautions must be observed to avoid distorting the upper frequency response of the accelerometer. For optimum response, it is recommended that the mounting surfaces and tapped holes conform as a minimum requirement to the following specifications:[4,5]

Surface flatness (Taper) ....700 μin., rms or less.

Surface finish ....125 μin., rms or better.

Perpendicularity of tapped hole ....±1°

To prevent damage to the accelerometer or possible distortion of the response, care should be taken to avoid "bottoming" the mounting stud in the accelerometer. Many manufacturers now supply a mounting stud with a flange or shoulder that prevents "bottoming" of the stud in the accelerometer. To ensure valid data at frequencies above 5000 Hz, it is recommended that a lubricant, such as silicone grease or a light oil, be used between the base of the transducer and the structure. With some types of accelerometers the mounted resonance frequency may be reduced as much as 10,000 Hz when no lubricant is used between the mating surfaces, figure 15. This results in an error of approximately 5% in the response at a frequency of 10,000 hertz. The percent error introduced when no lubricant is used will vary depending upon the mounting surface condition, the mounting torque applied, and the mounted resonance frequency of the accelerometer. Since the mounting torque used to attach the accelerometer depends upon the size of the mounting stud, it is advisable to use the torque recommended by the manufacturer. To ensure repeatable results, a torque wrench should be used to mount all accelerometers.

INSULATED STUD MOUNTING

A problem frequently encountered in making low (g) level noise measurements is the noise generated by ground-loop currents. Such currents are generally caused by a difference in potential between the accelerometer and amplifier grounds. This potential difference produces ground currents which result in noise and hum in the measuring system. Electrical noise of this type can severely restrict the low (g) vibration measuring capabilities of the system. One of the most effective methods of decreasing the influence of ground loops is to isolate the accelerometer electrically from ground by attaching it to the structure by means of an insulated stud. Several of the commercially available insulated studs are shown in figure 16. One disadvantage of the insulated stud is that it reduces the mounted resonance frequency of the accelerometer below that obtained with solid (regular) stud mounting. As a consequence, the usable upper frequency range of the system is also reduced as shown by figure 17. Since the upper frequency response will vary somewhat depending upon the vibrational characteristics of the insulated stud and accelerometer, it is recommended that the accelerometer/stud combination be calibrated to determine the true system performance. It is recommended also that a lubricant be used on all interfaces. If the lubricant used with the insulated stud is conductive, care must be taken that it does not create an electrical short across the insulating material of the stud.

The mounting torque recommended by the manufacturer, usually 18 to 25 in-lb, should not be exceeded. Applying torque greater than that recommended may result in shearing of the insulation material sandwiched between the metal bearing plates of the stud. Damage of this type, if undetected, will result in severe distortion of vibration measurements obtained at high frequencies. Insulated studs having hexagonal flanges are usually less susceptible to shearing damage. With the hex-flange construction, torque can be applied to the accelerometer side and the fixture side separately without introducing shear torque across the insulating medium.

On occasions where it may be necessary to shorten the length of the stud, care must be taken to avoid "shorting out" the insulating material between the stud flanges. This is usually caused by metallic particles that become deposited on the insulating material and form a conductive path. To determine the condition of the electrical insulation, an ohmmeter may be used to check for continuity across the stud flanges.

MOUNTING ADAPTERS

Most accelerometers used for structureborne-noise measurement are designed to be stud mounted directly to the part or structure undergoing investigation. In practice, however, there are many surfaces and systems where a threaded mounting-hole cannot be tolerated. As a consequence, methods such as cementing studs, double-faced adhesive tape, and magnetic-mounting must be considered. The required efficiency of the mounting adapter depends on the practical requirements of the accelerometer system. For the accelerometer to generate accurate data, the mounting adapter must remain rigid over the frequency range of interest and must be unaffected by the environment to which it will be exposed.

CEMENTING STUDS

In applications where the surface cannot be drilled and tapped to accept normal threaded studs, a cementing stud or adapter, figure 18, may be used to attach the accelerometer. Use of the adapter rather than cementing the accelerometer directly to the part under investigation, prevents contaminating the accelerometer.mounting threads with adhesive and also facilitates removal of the accelerometer. The type of adhesive used to attach the adapter depends on the individual application. Where the mounting surface may be irregular, or where the transducer may be subjected to high humidity, some authorities recommend the use of dental cement to attach the adapter. For more regular surfaces, and those not subjected to moisture or immersion, an adhesive such as Eastman 910 or one of the epoxy resin adhesives may be found suitable. Since adhesive types display wide differences in their response to the service conditions encountered, it is advisable to evaluate the adhesive prior to the application to make certain it satisfies the mechanical and environmental requirements.

The efficiency of the cementing stud attachment technique depends on several factors, namely, the rigidity of the adhesive, the dimensions of the stud flange (or adapter), and the care taken in preparing the surfaces to be bonded. For best results, the prepared surfaces must be free of all grease and loosely held contaminants. Sufficiently clean surfaces can usually be obtained by thorough degreasing or by wire brushing.[6] In general, the application of an adhesive to a painted surface is not to be recommended, since the adhesive bond will be only as strong as the bond of the paint to the substrate. For improved performance, it is desirable to remove the paint film, by abrasion or solvent action and apply the adhesive to the exposed substrate after a suitable pretreatment. Most bond failures can be traced to inadequate surface preparation or poor execution of an otherwise suitable bonding or curing technique.

In lieu of using the commercially available cementing type studs some investigators prefer to fabricate their own cementing studs or adapters. This permits them to tailor the adapter to the materials and dimensions best suited for a particular application. Since the materials and dimensions of the cementing stud or adapter become increasingly critical with frequency,[7] thorough evaluation of the adapter is recommended over the frequency range of interest. The response curves shown in figure 19 illustrate the effect of the dimensions of the cementing adaptor on the upper frequency of the accelerometer.

As noted earlier, the type of adhesive used to attach the accelerometer mounting adapter depends on the individual application. Consideration must be given to such influences as moisture, oils, solvents, hydraulic fluids, or chemical atmospheres that may be encountered. Other practical factors often involved are the toxicidy of the adhesive, the drying time and temperature, and the strength at various temperatures. Some adhesives form hard, brittle bonds which fail under vibratory conditions. At high temperatures all adhesives lose some of their strength and some types soften or decompose to the extent that they become useless.

One of the most versatile types of adhesive materials used to bond the mounting adapter, is the epoxy resin adhesive. Being a synthetic material, the adhesive may be formulated to meet a variety of service requirements and environments. For room temperature applications, an epoxy adhesive is available that will develop a strong, rigid bond in approximately 5 minutes. For high-temperature applications, thermosetting epoxy adhesives are available that produce rigid and mechanically strong bonds at service temperatures approaching 500° F.[8] The combined effect of high-temperature and high-frequency on the compliance of two types of thermosetting adhesives is illustrated by the response curves presented in figure 20. The differences in response displayed by the two adhesives emphasizes the need for dynamic evaluation of the adhesive prior to application to make certain it will not degrade the upper frequency response of the accelerometer. Where electrical isolation of the accelerometer is desirable, the mounting adapter may be bonded with an epoxy resin adhesive that is nonconductive. Thus, the adapter and accelerometer may be electrically isolated from ground.

TAPE MOUNTING

The use of double-coated adhesive tape for attaching the accelerometer is not generally recommended. Studies conducted by this laboratory and others have shown adhesive tape mounting to be unreliable where precise vibration measurements are required. One of the shortcomings to this method of attachment is the inability to fully determine and control the strength or rigidity of the adhesive bond. Some of the factors affecting the adhesive bond strength, and thus the accelerometer response, are variations in the tape thickness, variations in the adhesive, and in the pressure applied in attaching the accelerometer. As a result of such variables, vibration data obtained with the accelerometer tape mounted cannot be considered valid, particularly at the higher acceleration levels.

MAGNETIC ACCELEROMETER MOUNTING CLAMPS

In making structureborne-noise measurements, magnetic clamps, figure 21, are often used to attach the accelerometer to locations where drilling and tapping of the structure is prohibited. Magnetic clamps are also used because of the simplicity of attaching and relocating the accelerometer. If the structure being investigated is of ferromagnetic material, the accelerometer is stud-mounted to the magnet and the magnet placed directly on the measurement point. Where the structure under study is not ferromagnetic, the accelerometer and magnet may be placed on a steel mounting adapter which is then epoxy bonded to the measurement point. Because of the relatively large contact surfaces of the magnet-to-fixture interface, small variations in the physical conditions of the surface have a degrading effect on the accelerometer frequency response. Thus, in some applications the steel mounting adapter is employed for the sole purpose of providing a smooth, flat surface for attaching the magnetic clamp and accelerometer. In general, the use of the adapter is preferred over direct attachment of the magnet. For most applications use of the adapter will result in improved frequency response and improved measurement repeatability. The use of grease between the magnet feet and the contact surface is also recommended to ensure optimum response.

One disadvantage of the magnetic clamp method of attachment is that the addition of this new spring-mass element in series with the accelerometer lowers the natural mounted resonance of the accelerometer, thus reducing the useful upper frequency range at which data may be taken.

The response curves of figure 22 show how magnetic attachment limits the upper frequency range capabilities of the accelerometer system. For noise applications where a 2-dB increase in accelerometer sensitivity is not objectionable, the upper frequency limit of a 1-inch-diameter magnetic clamp (under ideal mounting conditions) is considered to be 8 kilohertz.[9] This frequency limitation applies to a particular size and type of magnet/accelerometer combination. The dotted curve of figure 22 was obtained with the 1-inch diameter magnet mounted on a 1 1/4-inch-diameter by 3/8-inch-high steel mounting adapter. The test accelerometer used with this assembly weighed 32 grams and had a normal stud mounted resonance of 32 kilohertz. When it is found necessary to use a magnet to attach the accelerometer, it is recommended that precautions be taken to ensure the adequacy of the magnet/accelerometer combination for measurements at the frequencies of interest.

For the magnetic mounting clamp to develop its maximum strength it is important that both the magnet feet and the contacting surfaces be clean and free from all forms of foreign material. In order to maintain the magnet at its maximum strength, it is important that a keeper (a flat piece of iron or steel) be kept in place across the poles of the magnet at all times when the magnet is not being used. Magnets can also lose strength if they are dropped, heated to very high temperatures, or subjected to strong magnetic fields such as those produced by large ac motors and transformers.

BASE BENDING SUSCEPTIBILITY

For the accelerometer to generate accurate and useful data it must respond only to acceleration applied along its sensitive axis with all other responses being negligible. While most accelerometers respond in this manner, some types respond also to strains induced in the crystal sensing element by base bending. Because of the intimate attachment of the accelerometer to the specimen, any deformation of the specimen surface will be transmitted to the sensing element, causing it to generate a signal. Since only very small displacements are required to generate output signals from the crystal, the error due to base bending may be as great as +35.0 to –24.0 dB for some types of accelerometers.[10]

In general, the susceptibility of an accelerometer to base bending will depend primarily on its basic construction. Accelerometers of the shear-type design normally have a much lower base bending sensitivity than the compression type accelerometer. Reference to figure 23 shows the sensing element of the shear type to be post mounted and thus relatively free from base deformations. By contrast, the crystal of the compression unit is in intimate contact with the base and will respond to base strains imposed by elastic deformation of the specimen surface.

Base bending sensitivity is defined as the error output from an accelerometer caused by strains induced in its base by deformation of the surface to which it is attached. It is standard practice to then specify the strain sensitivity as an equivalent (g) at some fixed level of strain. The Instrument Society of America Standard RP 37.2 sets the reference strain, against which accelerometers should be compared, at 250 μin/in.[11] However, since accelerometer strain sensitivity is not a linear function of specimen strain, the 250 microstrain is purely an arbitrary reference upon which the user can exercise an engineering judgement. In addition, compensation for error output due to base bending is usually impractical or impossible because of the effects of other variables such as surface conditions, mounting torque, and accelerometer base orientation with respect to the strain input. As a consequence, many investigators resort to the use of some type of mounting adapter between the accelerometer and specimen interface to ensure valid data. For example, in applications requiring the use of a high output, compression type accelerometer, it is found that error output may be minimized by attaching the accelerometer with an insulated stud.[12] When a relatively lower acceleration sensitivity is not objectionable, error due to elastic deformation of the surface may be minimized by the use of a shear-type accelerometer.

CABLES

One of the weakest links in the accelerometer system, and one that probably receives the least attention, is the cable used to connect the accelerometer to the amplifier or signal-conditioner. The coaxial cable used for this purpose must be small, light, and flexible and yet rugged enough to withstand the environment in which it is to be used.

TRIBOELECTRIC NOISE

One of the primary causes of cable noise is the triboelectric effect that occurs in some cables. When the cable is flexed or mechanically distorted, the resulting triboelectric charges may produce a signal pulse at the amplifier. In some low-frequency applications, the cable may generate a noise signal greater than that originating from the accelerometer. For this reason, it is important that the cable used to connect the accelerometer to the amplifier be as free as possible from triboelectric noise. In the low noise coaxial cable, triboelectric noise is minimized by applying a semiconductive coating between the dielectric and shield which dissipates electrical charges generated by repeated flexing of the cable. The coating process reduces noise voltage magnitude by a factor of more than 100 to 1.

SPURIOUS SIGNALS

In addition to good noise characteristics the cable should be sufficiently flexible to avoid mass loading the accelerometer case. The use of a massive or stiff cable may cause mechanical deformation of the accelerometer case. If the accelerometer is case sensitive, this force will be transmitted to the crystal causing it to produce a spurious electrical signal. For the case sensitive accelerometer, cable termination and routing can also be important. At low frequencies, with associated higher amplitudes, whipping of the cable will strain the cable at the connector and cause spurious signals in the transducer. This type of problem can usually be avoided by using a shear type accelerometer which is much less sensitive to cable induced strains. Many times it is found that cable strain can be alleviated by simply rerouting the cable. There is no specific method or technique that can be recommended for cable routing. A rule of thumb used by some investigators is to let the cable take its own straight line position as long as its weight does not become excessive. Others recommend that the cable be tied down within 2 or 3 inches of the accelerometer to alleviate strain due to cable whip.

ENVIRONMENT

In high-temperature applications the temperature characteristics of the coaxial cable are as important as those of the accelerometer. Both must operate in the same environment. Cable for general use will usually withstand temperatures ranging as high as 200° F before showing signs of deterioration. At higher temperatures changes in cable-capacitance occur that, in turn, cause the sensitivity of the system to vary. For high-temperature applications specialized cable is available that will function in temperatures up to 900° F. Cables are also available that will function in temperatures as low as 450° F.

When measurements are to be obtained in a high humidity environment it may be advisable to seal the cable connector to prevent moisture from entering the assembly. Moisture at the cable-connector interface lowers the RC time constant of the system and hence results in degradation of the low-frequency response. The cable connector may be made impervious to moisture by applying a moisture-proofing compound to the mated connectors after installation. Silicone rubber and acrylic plastic are examples of sealants that may be used to moisture-proof the connectors.

CABLE CARE

The need for care in handling the coaxial cable cannot be overemphasized. One of the most frequent causes of transducer system failure is breakage of the coaxial cable at the connector due to improper handling. When attaching the cable to the accelerometer, always turn the connector nut onto the accelerometer receptacle. Turning the accelerometer into the cable connector may cause the pin in the connector to pull loose and jam into the accelerometer receptacle. This can result in loss of data and possible loss of the accelerometer until repairs can be effected.

In attaching the cable make certain that it is screwed tightly to the accelerometer receptacle. In a surprising number of cases data are lost because the connector was not properly secured. Hand tightening the connector is usually adequate. In high amplitude applications, however, it may be advisable to use small pliers to tighten the connector. As an additional precaution, a coating of adhesive may be applied over the connector to prevent it from loosening.

Connector contamination caused by ordinary handling is another potential contributor to error in low-frequency applications. Careless handling of the cable may leave fingerprint deposits on the connector, thus creating low impedance paths between signal and ground that effect the low-frequency response of the accelerometer system. To minimize error from this source, it is recommended that cable connector and accelerometer receptacles be cleaned before installing by dipping them in a volatile solvent such as acetone.

When a cable problem is encountered, the insulation resistance of the suspected cable can be measured by means of a megohmeter at 50 or 100 volts. Continuity of the shield and center conductor can be checked by means of an ohmeter. Cable capacitance can be measured with a capacitance bridge or a capacitance meter. Often it is found that the problem can be solved much more quickly, however, by substituting another cable for the suspected faulty one.

PROBLEMS

GROUND-LOOP CURRENTS

Ground-loop currents represent a problem and source of error encountered in measuring low-level structureborne noise. Ground-loop currents generally occur when the common connection in the system is grounded at more than one point, figure 24. The difference in potential between the grounding points will cause an electrical current to flow between the grounds, resulting in error signals in the output. Signals originating from this source severely restrict the low-level measurement capability of the system. Ground-loop currents are a particular problem in applications where long lengths of cable must be used since the electrical potential between the grounding points increases with the distance between the grounds.

The most effective method of preventing ground loops is to make certain that the entire measuring system is grounded at a single point. In general, the most satisfactory point for grounding the system is at the readout electronics. This requires that both the accelerometer and the matching electronics be insulated or removed from ground. The amplifier can usually be isolated from ground by placing it on some type of insulating material. The most effective way of electrically isolating the accelerometer is to mount it to the structure by means of an insulated mounting stud. With this technique the accelerometer crystal is still shielded by the metal case which is grounded to the circuit by the metallic braided shield surrounding the cable. If unjacketed cables are used, care must be taken to prevent the exposed metallic shield or the connector becoming grounded ahead of the readout electronics.

An internal isolation technique is also used by some accelerometer manufacturers to prevent electrical noise signals from being generated in the measuring system. With this method, the crystal is insulated from the case and connected to the insulated connector, thus providing a "floating" output. The accelerometer case is grounded to the structure and not to the signal ground. This technique, however, has one disadvantage. The capacitance coupling path between the case and sensing element permits coupling of ac noise directly into the accelerometer, resulting in possible error in the measurement.

ACCELEROMETER TRANSVERSE SENSITIVITY

Another potential source of error in the piezoelectric accelerometer, and one that some investigators consider most important, is the sensitivity of the accelerometer to motion applied perpendicular to its sensitive axis. The response of the acceleration transducer to acceleration forces in axes perpendicular to the sensitive axis, figure 25, is usually referred to as the cross-axis or transverse sensitivity of the accelerometer. The electrical output due to the transverse motion is usually expressed as a percentage of the axial (reference) sensitivity. Transverse sensitivity is primarily a function of the accelerometer mechanical design and manufacturing tolerances. Most new accelerometers have a relatively low transverse sensitivity of less than 5% of the axial sensitivity. When requested, some manufacturers will supply transducers with 1% (or less) transverse sensitivity.

Transverse or cross-axis sensitivity is determined by mounting the transducer to the vibration exciter so that sinusoidal motion is applied in a plane perpendicular to the sensing axis of the accelerometer. During calibration the transducer is rotated about its sensing axis through 360°, at increments not exceeding 60°.[11] Calibration is usually performed at a single frequency below 500 Hz because the majority of accelerometer calibrators themselves are extremely sensitive to transverse accelerations at higher frequencies. The variation in transverse sensitivity, as the accelerometer is rotated about its sensitive axis, describes a sinusoid as shown by figure 26. The maximum value shown by the curve is reported as the transverse sensitivity. This particular accelerometer is found to have a transverse sensitivity of less than 4%. Polar-coordinate plots may also be used to illustrate the sensitivity of the crystal accelerometer to lateral motion, figure 27.

Note how the electrical output varies with the angle of the applied vibration and that the output approaches zero as the accelerometer is rotated about its axis. This suggests that the maximum cross-axis sensitivity value obtained for the accelerometer is applicable for motion applied at one particular angle. Referring to figure 26 it can be seen also that the transverse output undergoes a change in polarity as the transducer is rotated about its sensitive axis. At an angular position of 90°, the maximum response has a positive polarity. When the transducer is rotated 180°, however, the maximum response assumes a negative polarity. Theoretically, the signal error resulting from transverse accelerations might vary from −6 to +6 dB (depending upon the ratio of axial to lateral acceleration). From a practical viewpoint, however, this is not likely to occur, since maximum transverse response is produced at one particular angle. Because of the variables associated with cross-axis sensitivity, it is impractical, if not impossible, to compensate for measurement error introduced by the random transverse acceleration forces encountered in field measurements. Fortunately, error from this source may be minimized by selecting accelerometers known to have a relatively low (3% or less) transverse sensitivity. It is important also to calibrate the accelerometer periodically to assure that the cross-axis sensitivity has not increased. Lateral sensitivity (and also axial sensitivity) may become altered if the transducer is subjected to severe shock by dropping or through other abuse.

ACOUSTIC SENSITIVITY

Although piezoelectric accelerometers are designed to respond only to accelerations applied to their mounting surfaces, it is well known that some models also respond to high-level acoustic pressures. Ordinarily, piezoelectric accelerometers have outputs of only a few (g) when exposed to high acoustic pressures so that good signal-to-noise ratios are obtainable in the majority of measurement applications. There are occasions, however, where low-level vibration measurements must be made on structures in high-level acoustic fields. Under these conditions attention must be given to the acoustic response of the accelerometer system.

Acoustic sensitivity is defined as the output of a transducer to a specified acoustical environment. The sensitivity is determined by mounting or suspending the accelerometer in a reverberant acoustical test chamber and subjecting it to a specific sound-pressure level spectrum covering the frequency range from 75 to 9600 hertz. Either a swept sinusoid or a random acoustic input may be employed.[11] The rms electrical output of the transducer is measured and converted to equivalent rms (g's) at a specified sound-pressure level spectrum. For example, the sensitivity may be given as 0.007 equivalent rms (g) at 140 dB sound-pressure level (referred to 20 μPa). Since many engineers and technicians prefer to express pressure in gravitational units of force per unit area, the same sensitivity may also be specified as 0.05 equivalent g/lb/in^2. One lb/in^2 rms is equivalent to approximately 170 dB sound-pressure level. To illustrate how the acoustic sensitivity term is related to error in the measured acceleration, assume the accelerometer to have an acoustic sensitivity of 0.05 g/lb/in^2 and the environmental sound pressure to be 170 decibels. At this pressure level we would expect the magnitude of the electrical signal due solely to the sound-pressure acting on the accelerometer to be 0.05 equivalent (g). Thus, even if there was no actual acceleration acting on the transducer, it would still indicate an acceleration of 0.05 g.

Since corrections for error due to acoustic sensitivity are not possible, the accelerometer must either be unaffected by the acoustic noise or the error due to the pressure must be small enough to be tolerated. Obviously, the maximum acceptable sensitivity is dependent upon the sound-pressure level to which the accelerometer is exposed, the percentage of error allowable, and the actual level of the acceleration to be measured.

ELECTROMAGNETIC SENSITIVITY

When vibration measurements must be made in or near strong magnetic fields, it is important that the accelerometer measuring system be insensitive to magnetic interference. Electromagnetic field sensitivity is defined as the maximum output of a transducer in response to a specified amplitude and frequency of magnetic field.[11] The response of the transducer to an electromagnetic field is determined by mounting it on a 10- to 15-pound plate of nonmagnetic material such as lead. The mounted transducer is then placed in a known magnetic field so that the sensitive axis of the transducer points toward the source of electromagnetic energy and the plate is away from the source. The transducer is then rotated about its sensitive axis to determine the maximum electrical output. This voltage is recorded as equivalent (g) per gauss based on the reference sensitivity of the transducer. Fortunately, most piezoelectric transducers are relatively insensitive to magnetic fields. Typical accelerometer magnetic sensitivities specified by one manufacturer range from 0.001 to 0.0001 g/gauss.

For a better understanding of accelerometer magnetic response, consider an accelerometer with a magnetic sensitivity of 0.001 g/gauss exposed to an a-c magnetic field of 25-peak gauss. An a-c field of this magnitude would cause the accelerometer to emit an error signal equivalent to an acceleration of 0.025 g or approximately 90 dB re: $1\mu g$. Obviously, an accelerometer with a magnetic sensitivity of 0.001 g/gauss would not be suitable for low-level noise measurements in an environment where it would be exposed to electromagnetic fields in the order of 25-peak gauss. One solution to this problem is to use an accelerometer less sensitive to magnetic interference. Another alternative might be to shield the transducer from the source of electromagnetic radiation.

Another problem that may be encountered in a magnetic environment is the spurious output caused by the accelerometer cable being vibrated by the changing magnetic flux. If the accelerometer is of the case-sensitive type, the spurious signals induced by the cable may be of such magnitude as to severely restrict the use of the system for low noise level measurements. The signal conditioner used in the system may also be significantly affected by magnetic fields. An increase of 20 dB in the residual noise level of the system is not uncommon when the signal conditioner is subjected to an a-c magnetic field of 24-peak gauss at 60 hertz.[1] To minimize error from this source it is recommended that the signal conditioner be kept as far away as practical from the ends of motors and other sources of electromagnetic radiation. In a very high intensity magnetic field it may be necessary to provide special shielding for the accelerometer, cable, and amplifier in order to obtain the required signal to noise levels and accuracies.

ACCELEROMETER RECALIBRATION AND MAINTENANCE

The piezoelectric accelerometer is not only a precision instrument, it is also a rugged one and under normal laboratory use its performance characteristics remain relatively stable. To ensure data accuracy, however, it is recommended that accelerometers be calibrated at least once a year even when used under laboratory conditions only. The calibration interval may vary depending upon the accelerometer usage. For accelerometers used in a high-temperature environment it may be advisable to calibrate at shorter intervals. Some laboratories base the recalibration interval on the number of hours the accelerometer has been exposed to elevated temperatures or to other environmental extremes. In addition to the normal maintenance calibration, some engineers find it desirable to recalibrate the transducer just prior to conducting the noise measurement. Needless to say, the more frequent the recalibration interval, the higher the degree of confidence in the noise measurement data.

The recalibration is usually performed by the comparison method in which the response of the test transducer is compared to a secondary standard accelerometer having traceability to the National Bureau of Standards. The accelerometer is calibrated over its useful frequency range to determine whether its reference sensitivity or frequency response characteristics have been altered. If there is evidence that the dynamic response characteristics of the transducer have been altered, capacity, resistance, and cross-axis recalibrations may be desirable to determine the nature and extent of possible damage.

As part of the maintenance program, regular inspections should also be made of the accelerometer case and base to detect dents, nicks, scratches, or other damage that may affect the response. Burrs or scratches on the mounting surface may increase the transverse sensitivity and restrict the upper frequency response of the transducer. The coaxial connector of the transducer should also be inspected for damage and possible contamination. All grease, oil, or dirt should be removed to ensure the proper insulation resistance and good low-frequency response. It is recommended that a permanent record of each accelerometer and its calibration be kept on file. Response data obtained at each recalibration interval can then be compared to the original response record to detect any change in the transducers reference sensitivity and performance. If abnormal response is suspected, the transducer should be removed from service and returned to the manufacturer for repair.

SUMMARY

The purpose of this report is to point out some of the variables known to affect the dynamic response of the piezoelectric transducer and to prescribe approved vibration measurement techniques that will ensure the accuracy and validity of the vibration data. Many of the techniques described evolved from behavior studies conducted by this laboratory. New concepts in the design and development of machinery, structural materials, and damping techniques have resulted in a significant reduction in the transmission of structureborne noise. This, in turn, has placed more stringent requirements on the piezoelectric transducer and calibration measurement techniques. To meet these new requirements, continuous studies are conducted by the Acoustic Transducer Research and Calibration Facility of the Annapolis Laboratory, Naval Ship Research and Development Center. These studies are directed toward the development of improved vibration and calibration measurement techniques, extension of the frequency range over which vibration measurements may be practically made, and the development of high precision, completely reliable accelerometers that will successfully meet increasingly severe service requirements. In addition, this laboratory performs both absolute and comparison type calibrations for transducers used in the Navy's vibration measurement programs, NSRDC laboratory projects, and for industry performing work for the Navy. The calibrations performed by this laboratory ensure tracability of the vibration measurement to standards established by the National Bureau of Standards. Questions regarding structureborne vibration measuring techniques, instrumentation, transducer calibration, or the performance characteristics of piezoelectric type transducers may be directed to the Officer in Charge, Annapolis Laboratory, Naval Ship Research and Development Center, Annapolis, Maryland, marked Attention Code 274.

TECHNICAL REFERENCES

1 - Maxwell, D., and P. O. Prendergast. "Evaluation of an Installed Noise Monitoring System Which Utilizes Two-Unit Signal Conditioning," NSRDC Rept 7-396 (June 1970)

2 - Sheridan, A. A., and R. W. Miller, "Development of a High-Temperature Calibration System for Vibration Transducers," NSRDC Rept 2432 (Sept 1967)

3 - Sheridan, A. A., and R. W. Miller, "Piezoelectric Accelerometer Error at High Temperatures," NSRDC Rept MACHLAB 55 (Dec 1968)

4 - "Sensivity Changes in Vibration Transducers Due to Surface Irregularities," NAVENGRXSTA R&D Rept 820006H (30 Aug 1961)

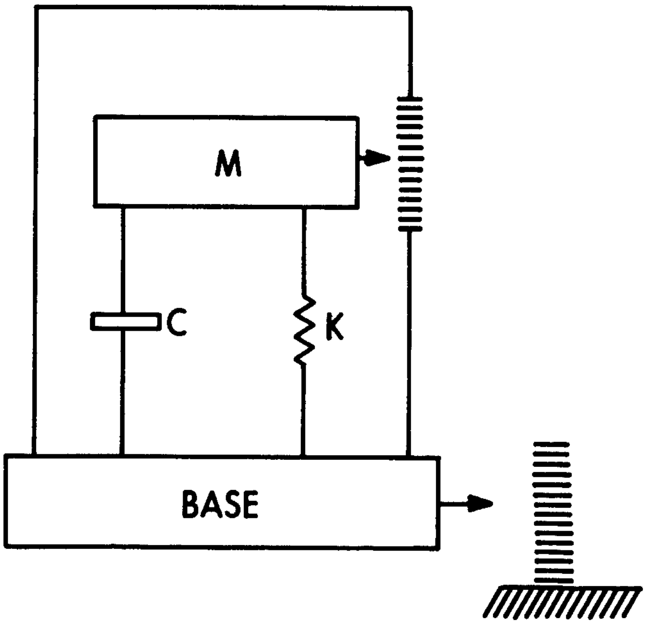
5 - "Airborne and Structureborne Noise Measurements and Acceptance Criteria of Shipboard Equipment," MIL-STD-740B (SHIPS) (13 Jan 1965)

6 - Shields, J., Scientific Instrument Research Association, Adhesives Handbook (1970)

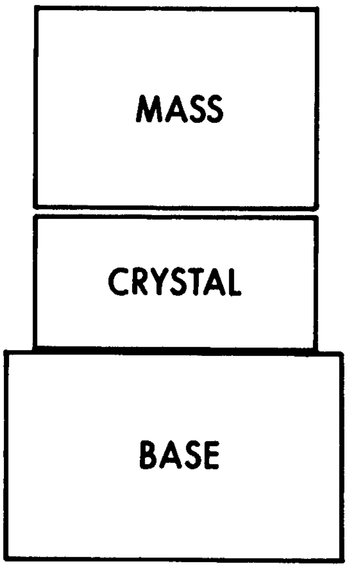
7 - Miller, R. W., and A. A. Sheridan, "High-Temperature/High-Frequency Limitations of Epoxy-Bonded Accelerometer Cementing Studs," NSRDC Rept 7-534 (Mar 1971)

8 - Miller, R. W., "High-Temperature/High-Frequency Response Characteristics of Two High-Temperature Epoxy Cements Used to Attach Accelerometer Mounting Blocks," NSRDC Rept 7-412 (June 1970)
9 - Sheridan, A. A., and R. W. Miller, "Frequency Response Characteristics of a Magnet-and-Accelerometer-Pad Mounting System," NSRDC Rept 7-427 (16 June 1970)
10 - Sheridan, A. A., and R. W. Miller, "The Influence of Structural Bending Upon the Acceleration Sensitivity of Accelerometers Used in Vibration Measurements," MEL R&D Rept 266/64 (Dec 1964)
11 - "Guide for Specifications and Tests for Piezoelectric Acceleration Transducers for Aero-Space Testing," RP 37.2, *Instrument Society of America* (1964)
12 - Sheridan, A. A., and R. W. Miller, "An Effective Decoupler for Suppressing Structural Bending in Accelerometers," MEL R&D Rept 146/65 (July 1965)

Item (a)
The Spring-Mass System



Item (b)
Basic Compression



Item (c)
Center-Post-Mounted

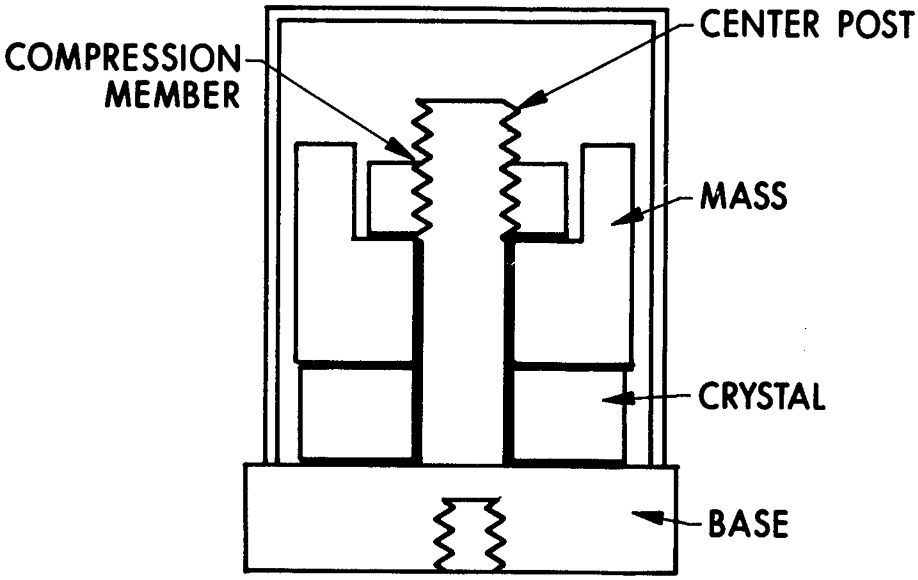


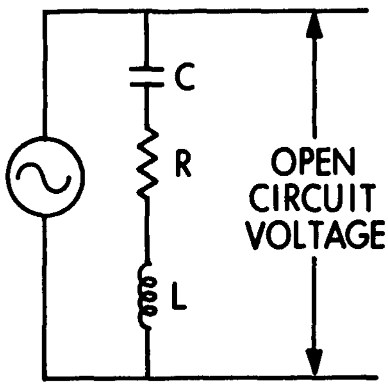
Figure 1
Basic Transducer Design

C_p = Crystal Capacity

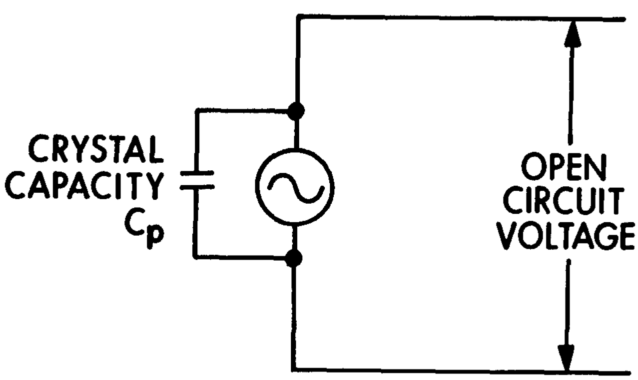
e = Open-Circuit Voltage

Q = Charge

Item (a)
Equivalent Circuit



Item (b)
Charge Generator Equivalent
$Q = e\ C_p$



Item (c)
Voltage Generator Equivalent
$e = Q/C_p$

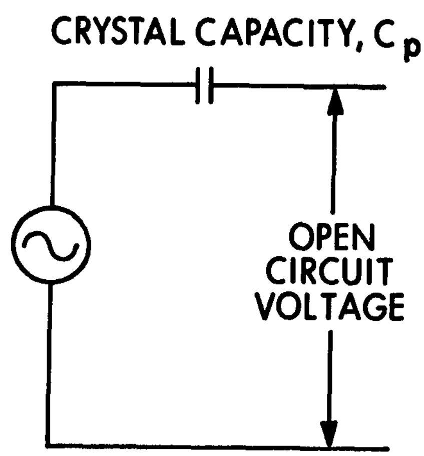


Figure 2
Accelerometer Equivalent Circuits

C_p = Crystal Capacity

C_c = Cable Capacity

C_f = Capacity of Feedback Capacitor

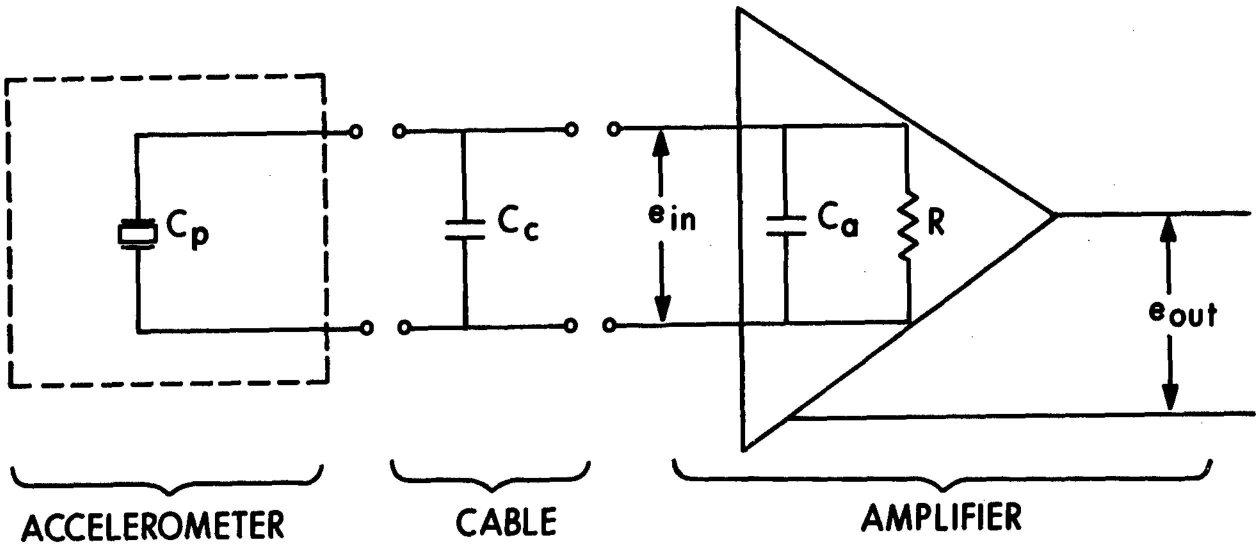
e_{in} = Voltage Input

e_{out} = Voltage Output

C_a = Amplifier Input Capacitance

R = Amplifier Input Resistance

VOLTAGE AMPLIFIER



CHARGE AMPLIFIER

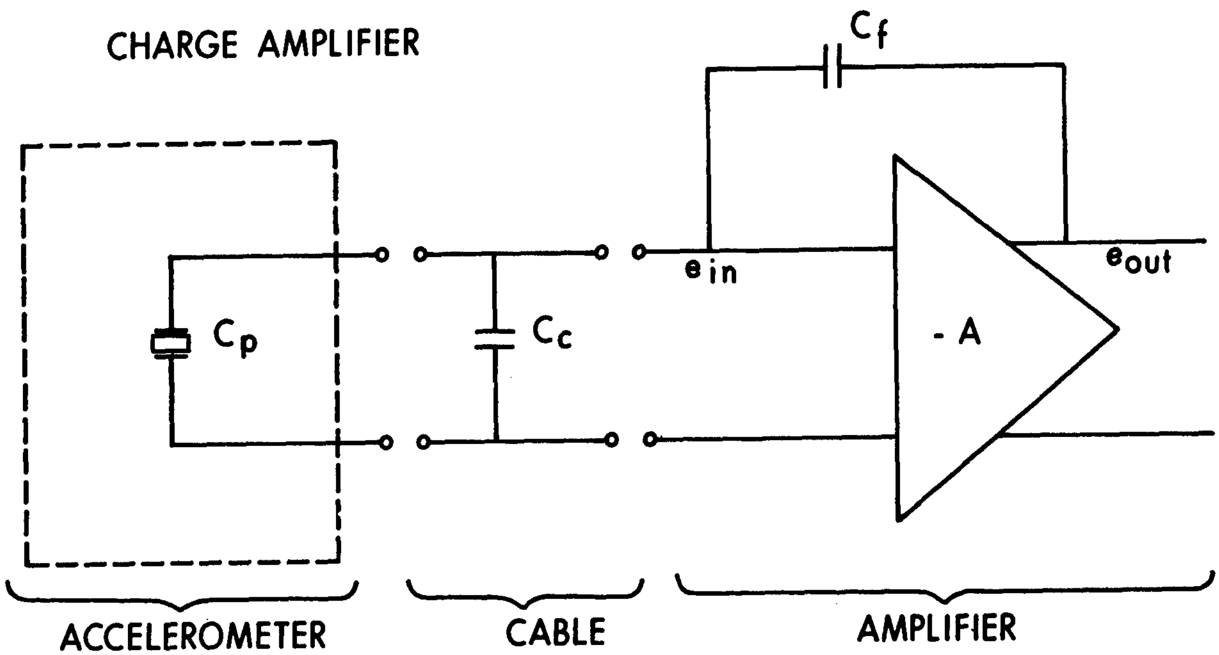


Figure 3
Accelerometer/Amplifier Equivalent Circuits

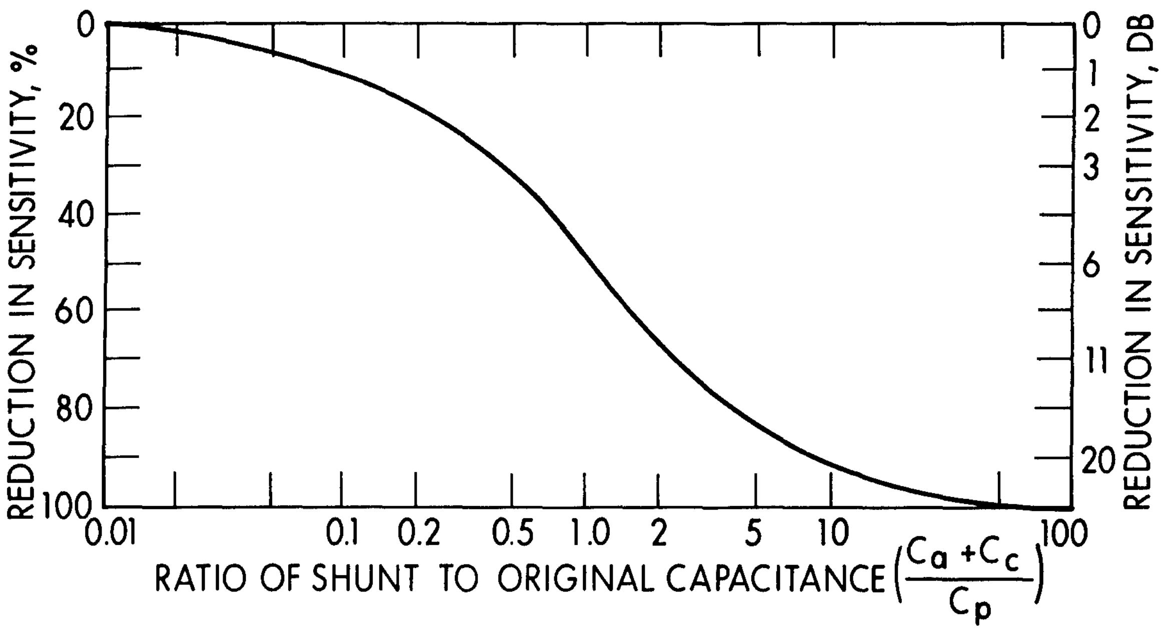


Figure 4
Reduction of Open-Circuit Voltage
Sensitivity Due to Shunt Capacitance

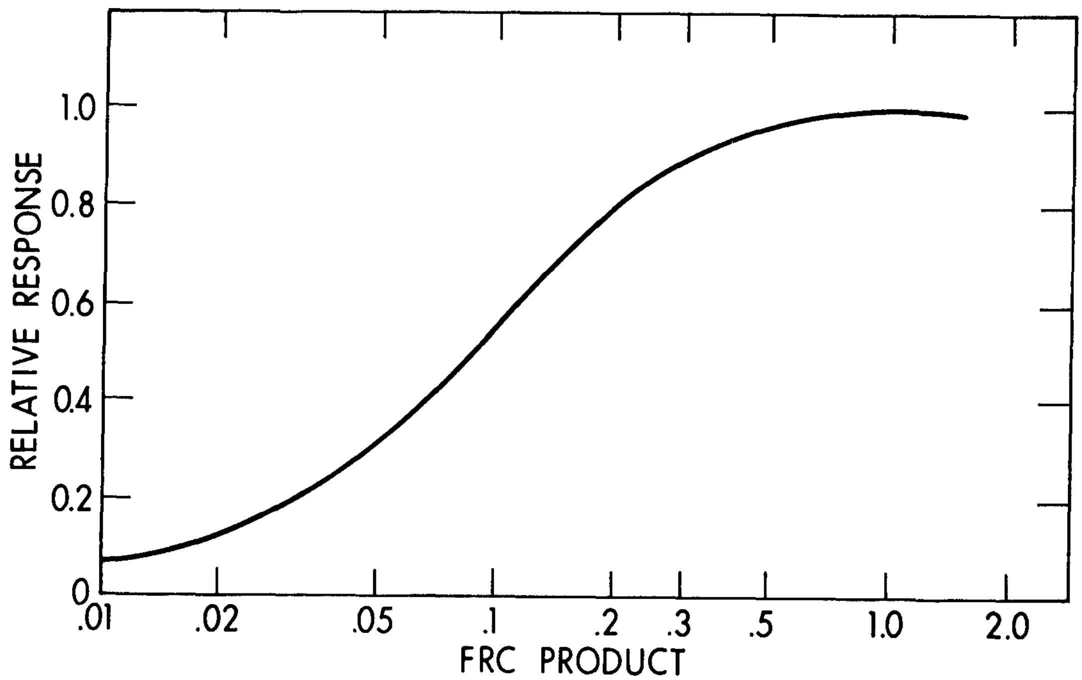


Figure 5
Relative Response Versus FRC Product

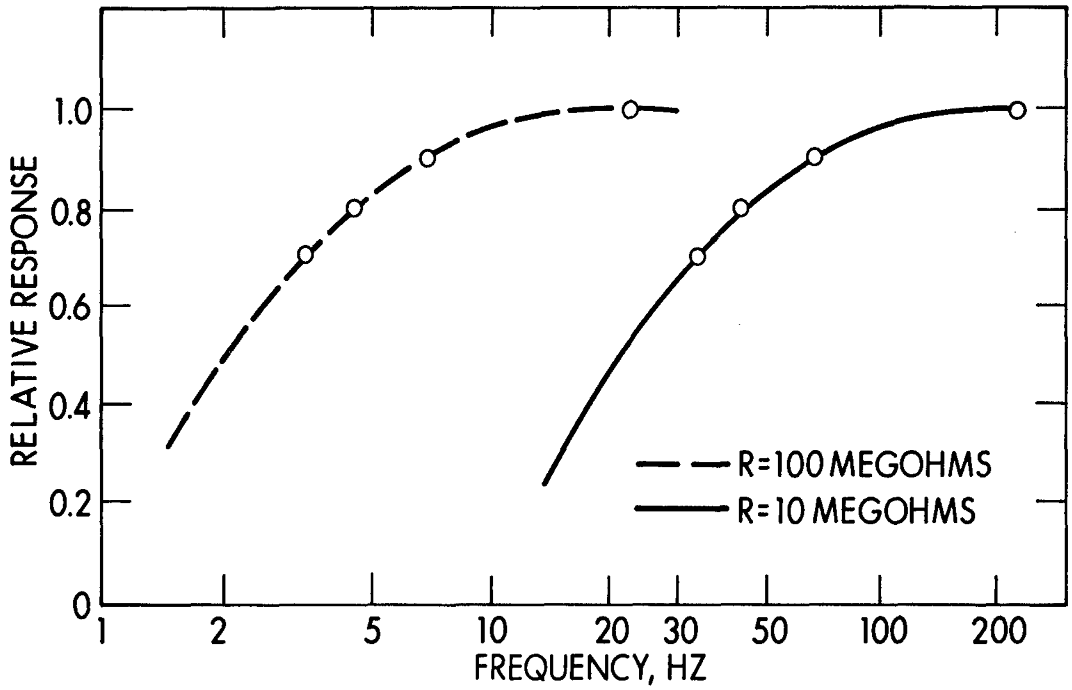


Figure 6
Effect of Shunt Resistance on Low-Frequency Roll-Off

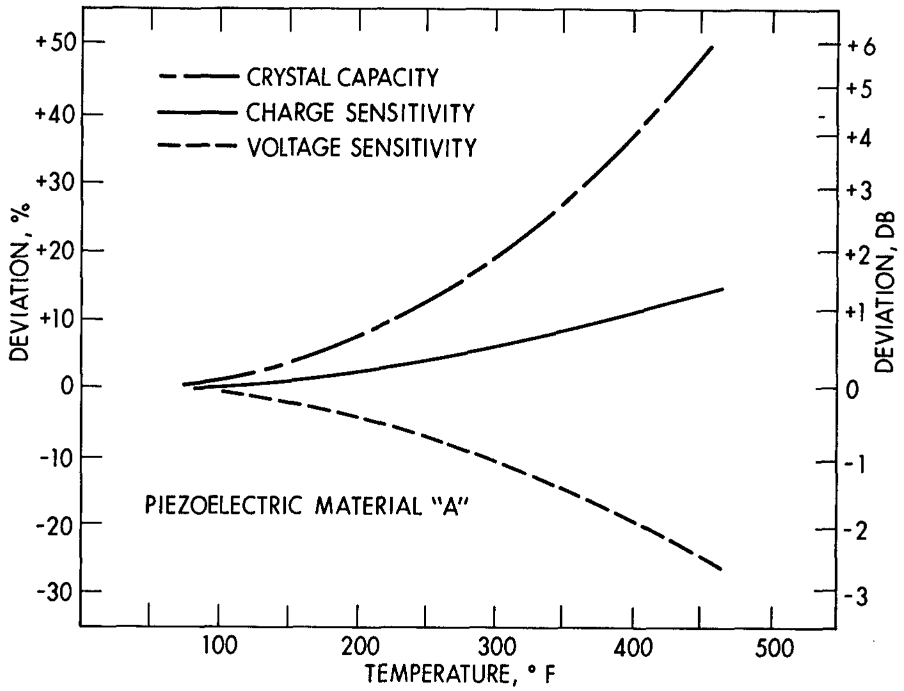


Figure 7
Accelerometer Temperature Response Characteristics

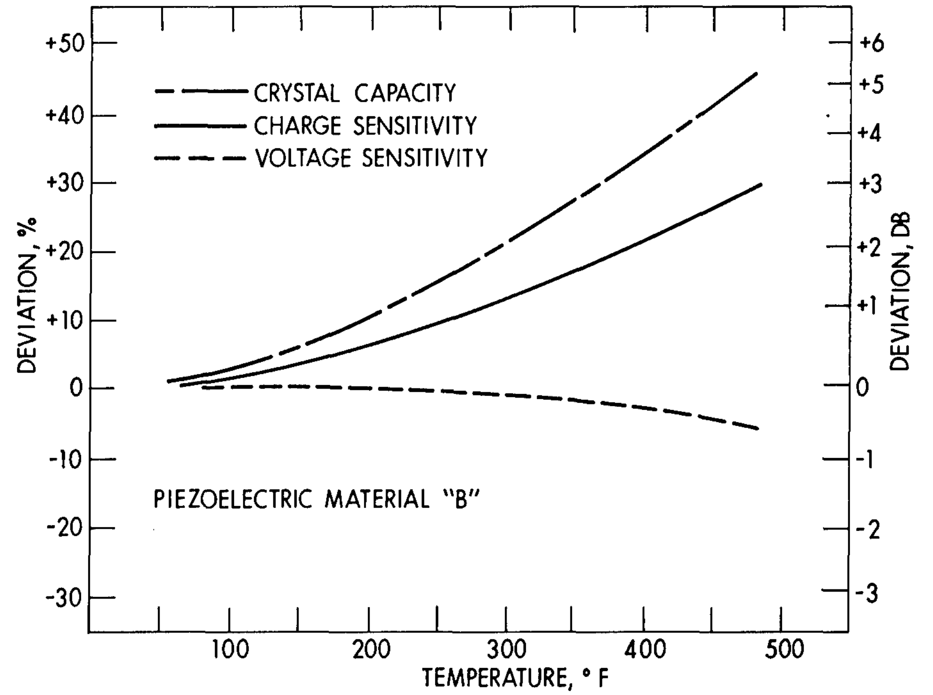


Figure 8
Accelerometer Temperature Response Characteristics

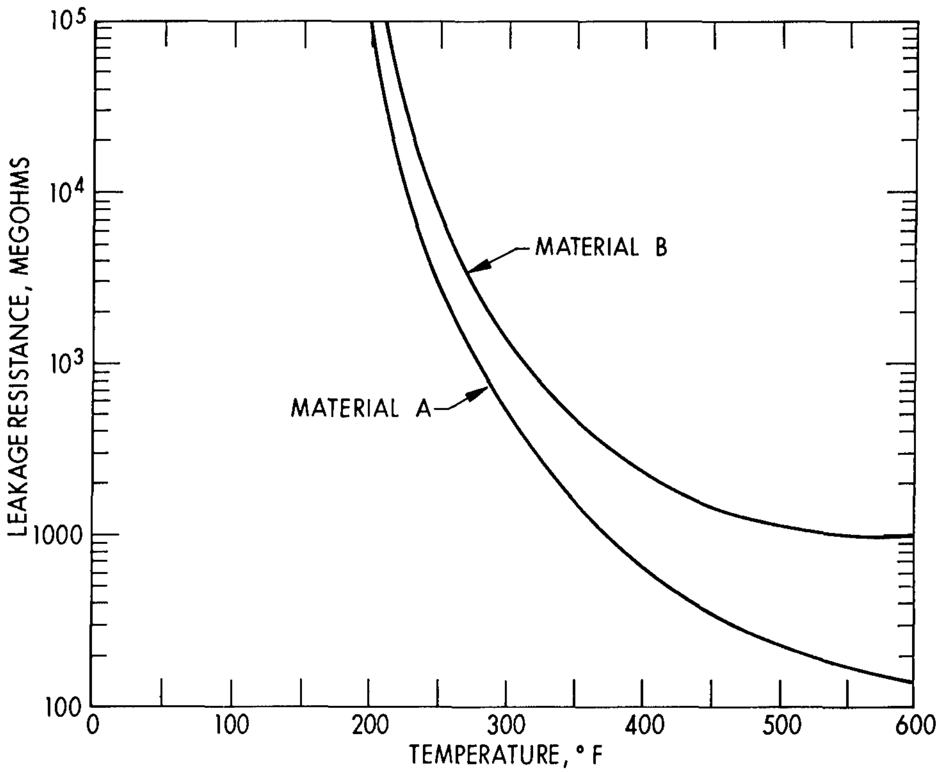


Figure 9
Effect of Temperature on Leakage Resistance

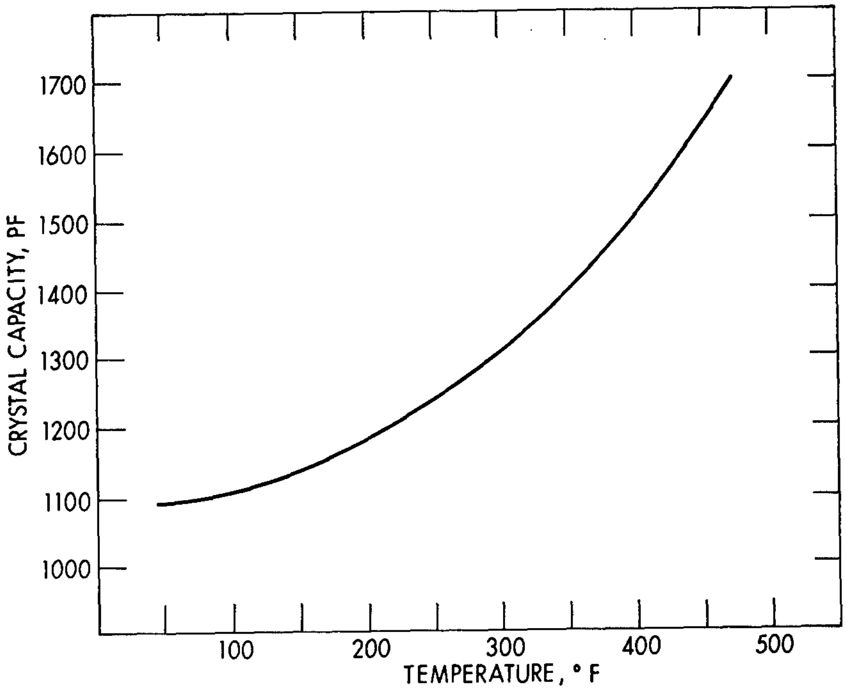


Figure 10
Effect of Temperature on Accelerometer
Crystal Capacity

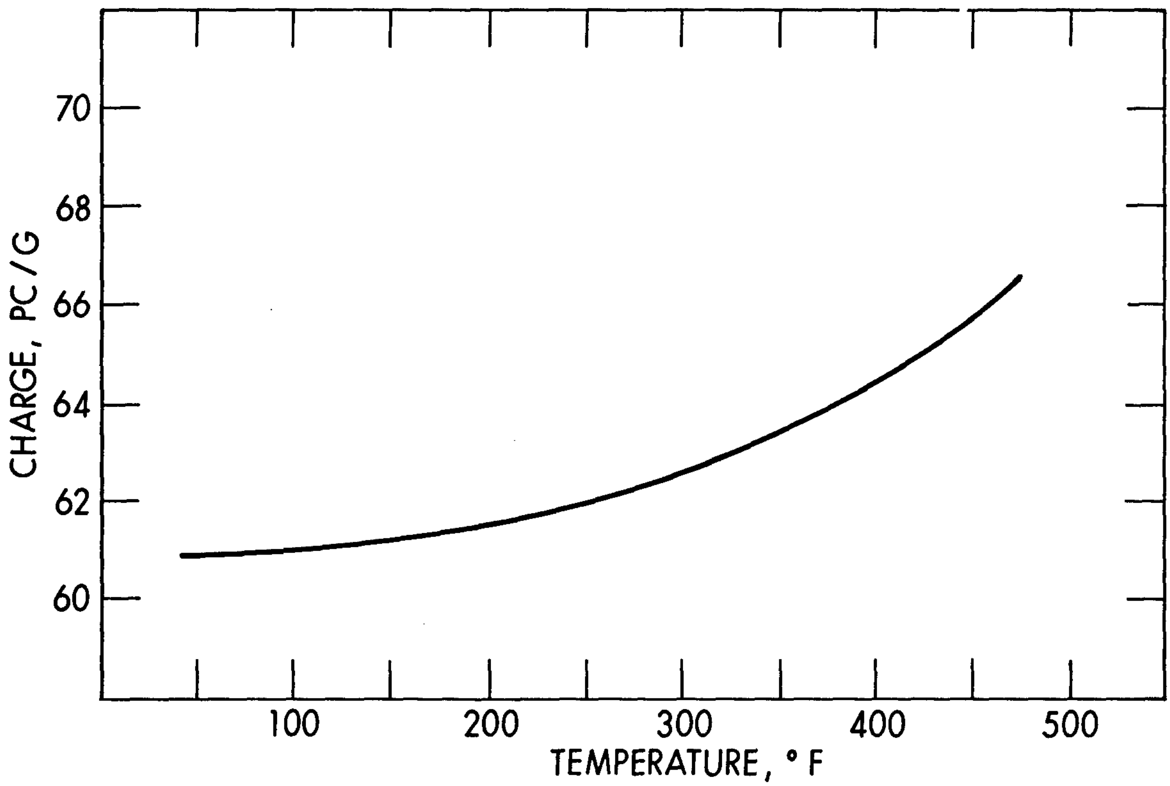


Figure 11
Effect of Temperature on Accelerometer
Charge Sensitivity

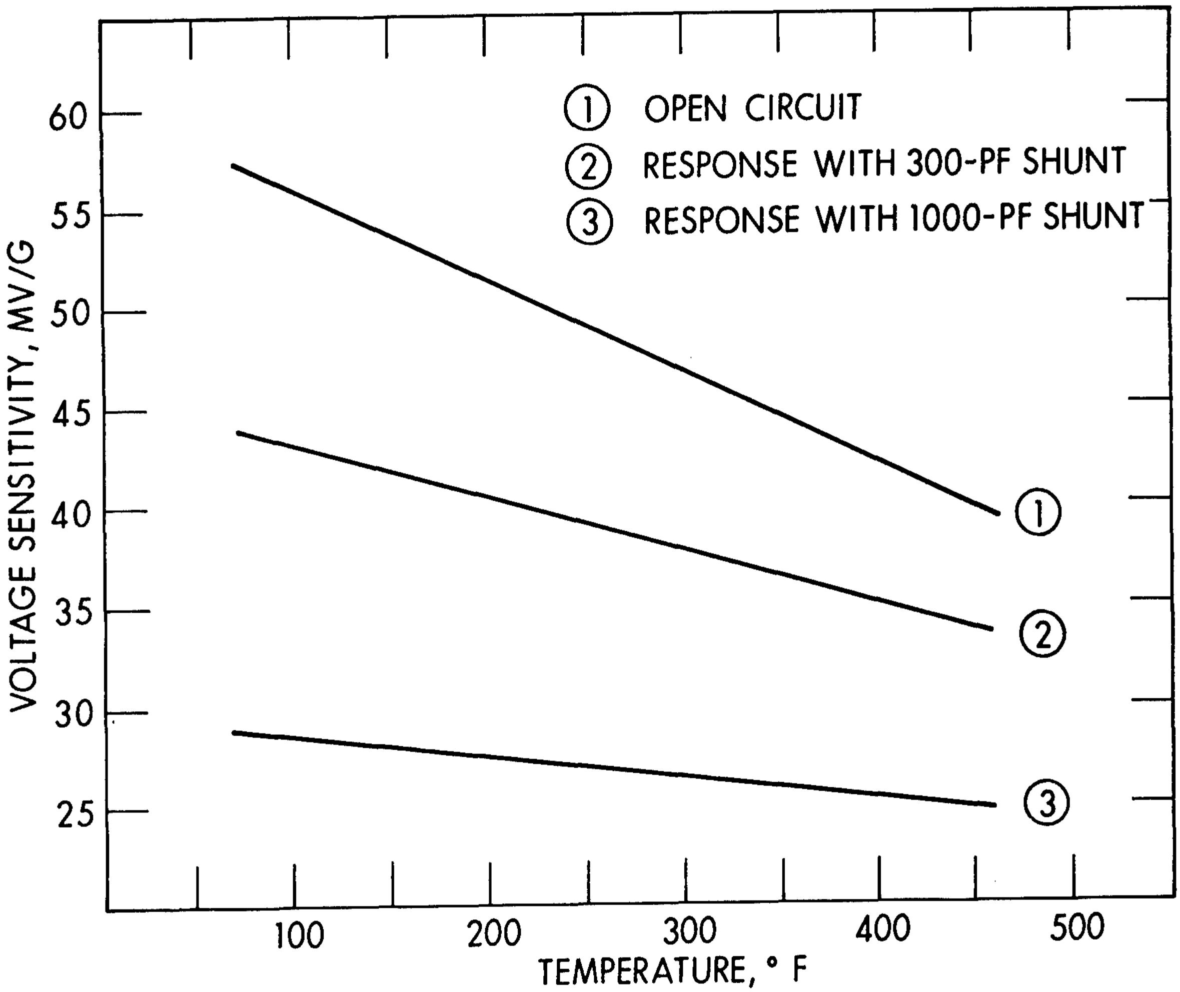


Figure 12
Effect of Increased Shunt Capacity
on Accelerometer Temperature Response

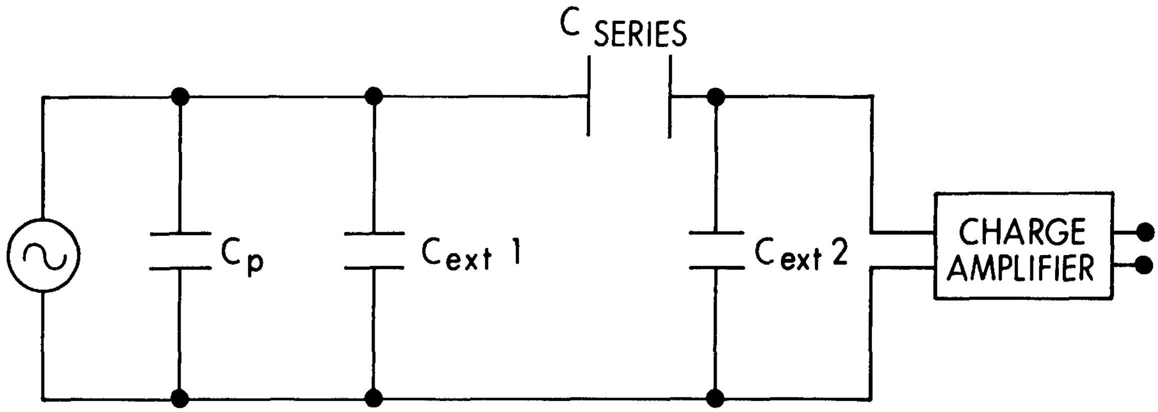


Figure 13
Accelerometer Charge Amplifier with Series
Compensating Capacitor

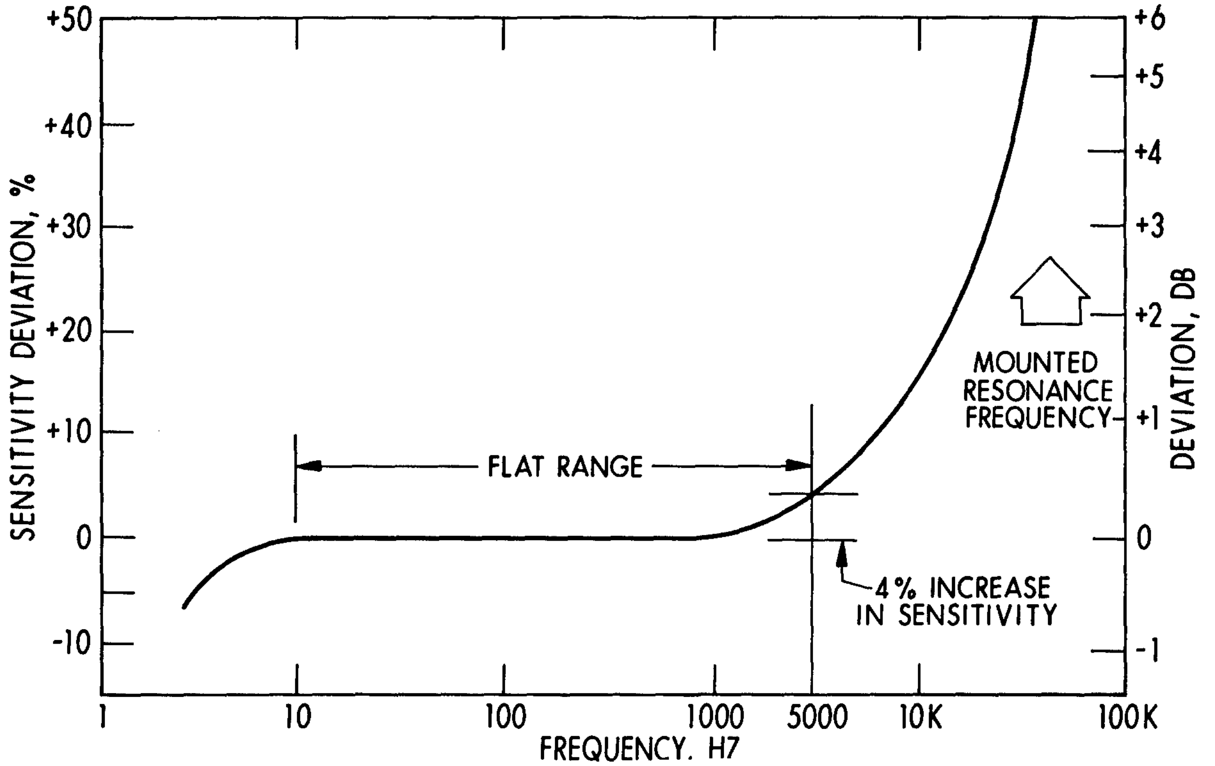


Figure 14
Typical Accelerometer High-Frequency Response

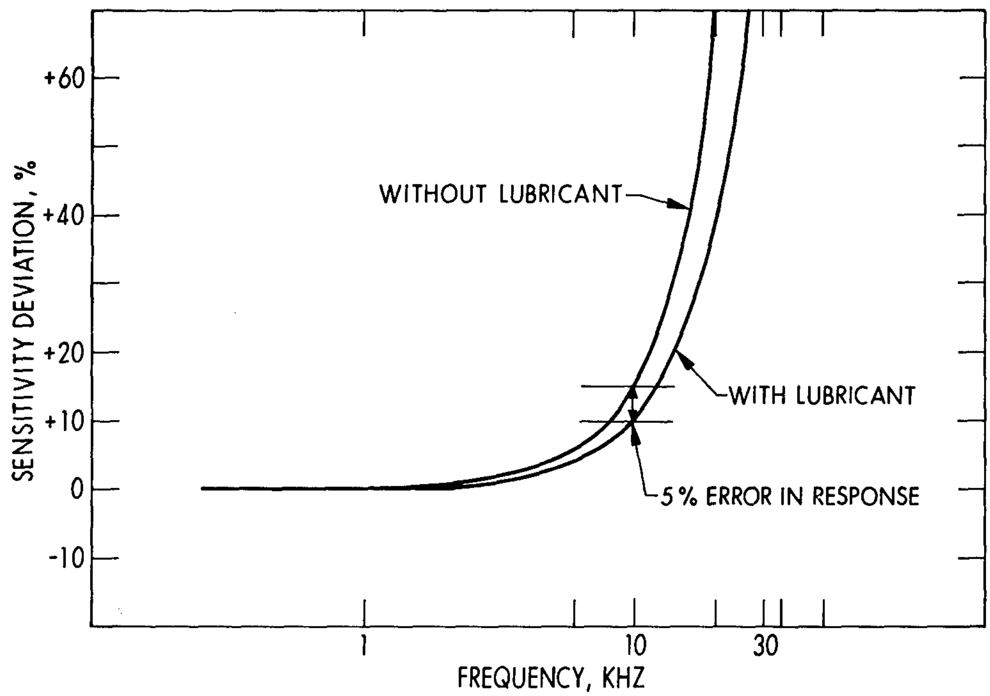


Figure 15
Effect of Lubricant on Accelerometer Response

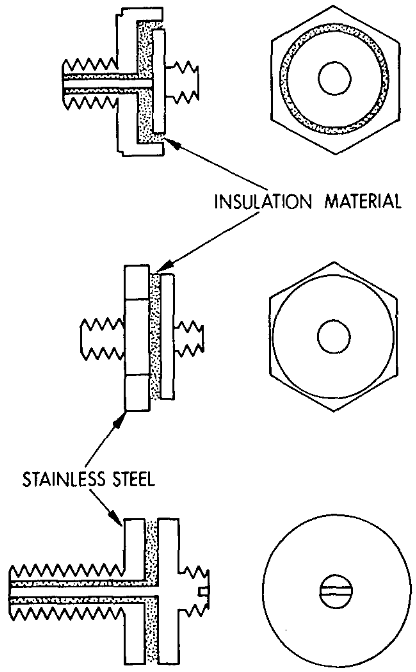


Figure 16
Insulated Mounting Studs

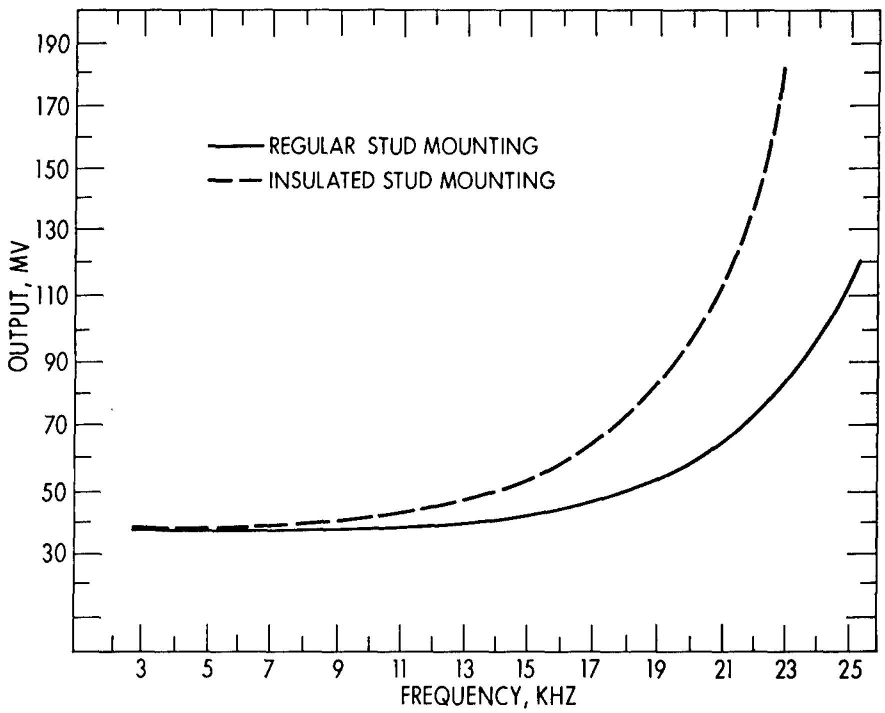


Figure 17
Effect of Insulated Stud Mounting
on Accelerometer Response

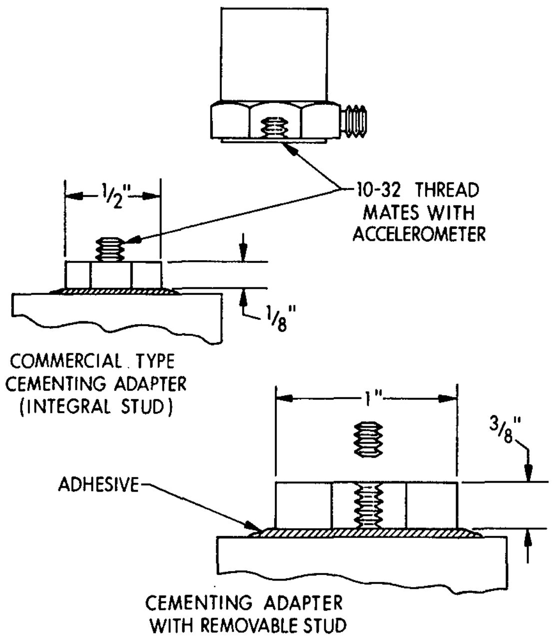


Figure 18
Accelerometer Mounting Adapters

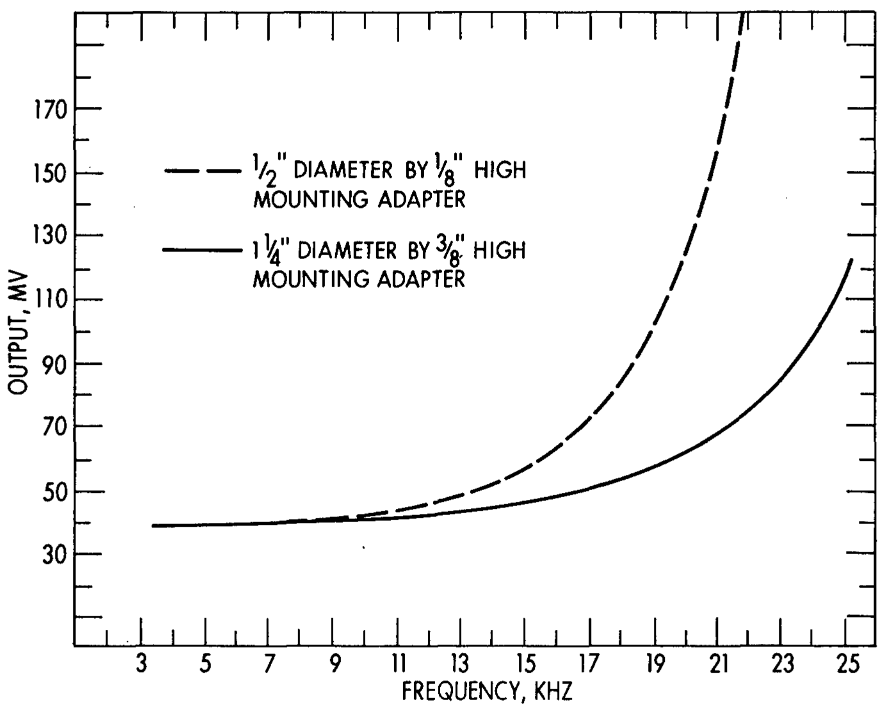


Figure 19
Effect of Mounting Adapter Size
on Accelerometer Response

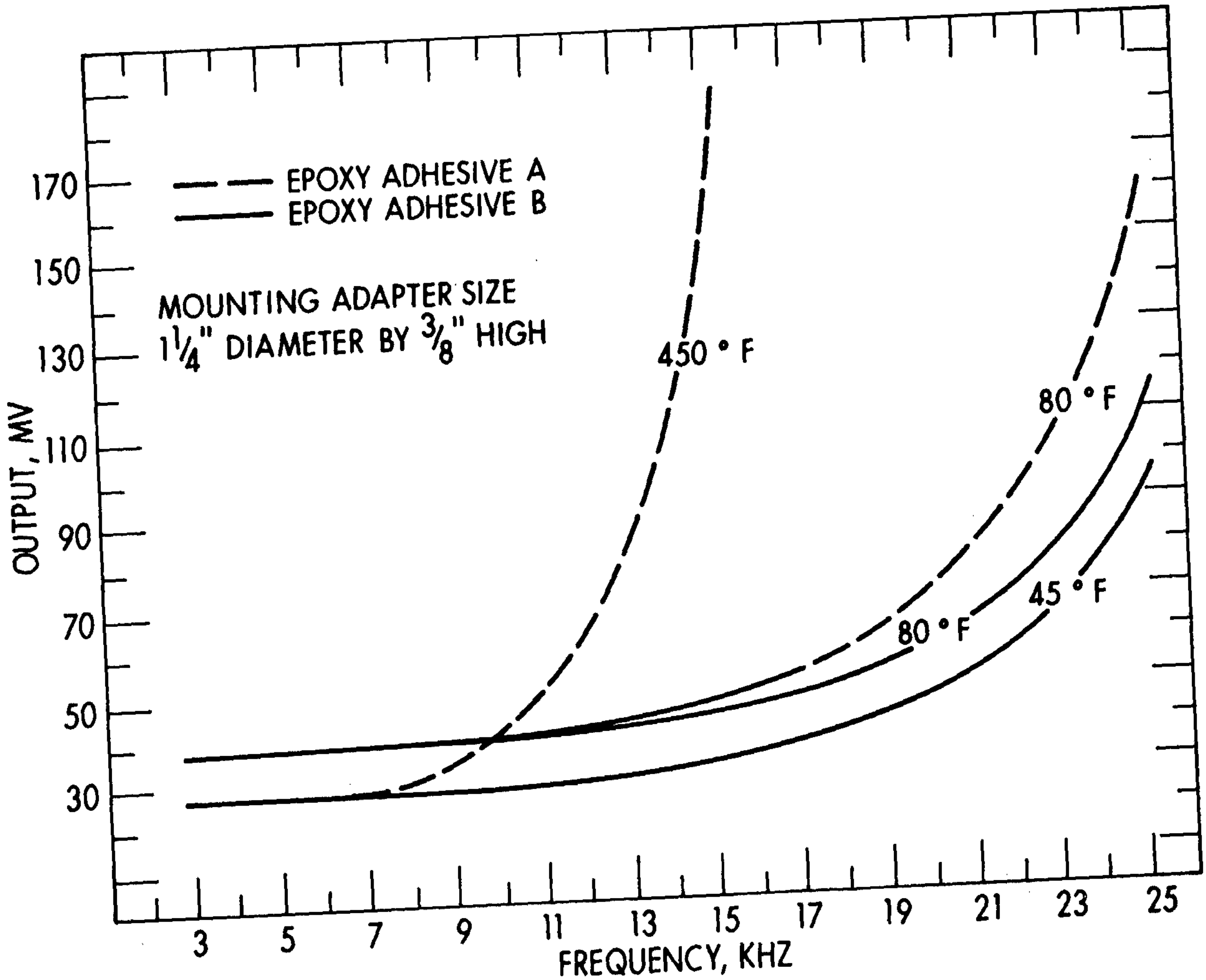


Figure 20
Upper Frequency Limitations of Two Types
of High-Temperature Epoxy Adhesives

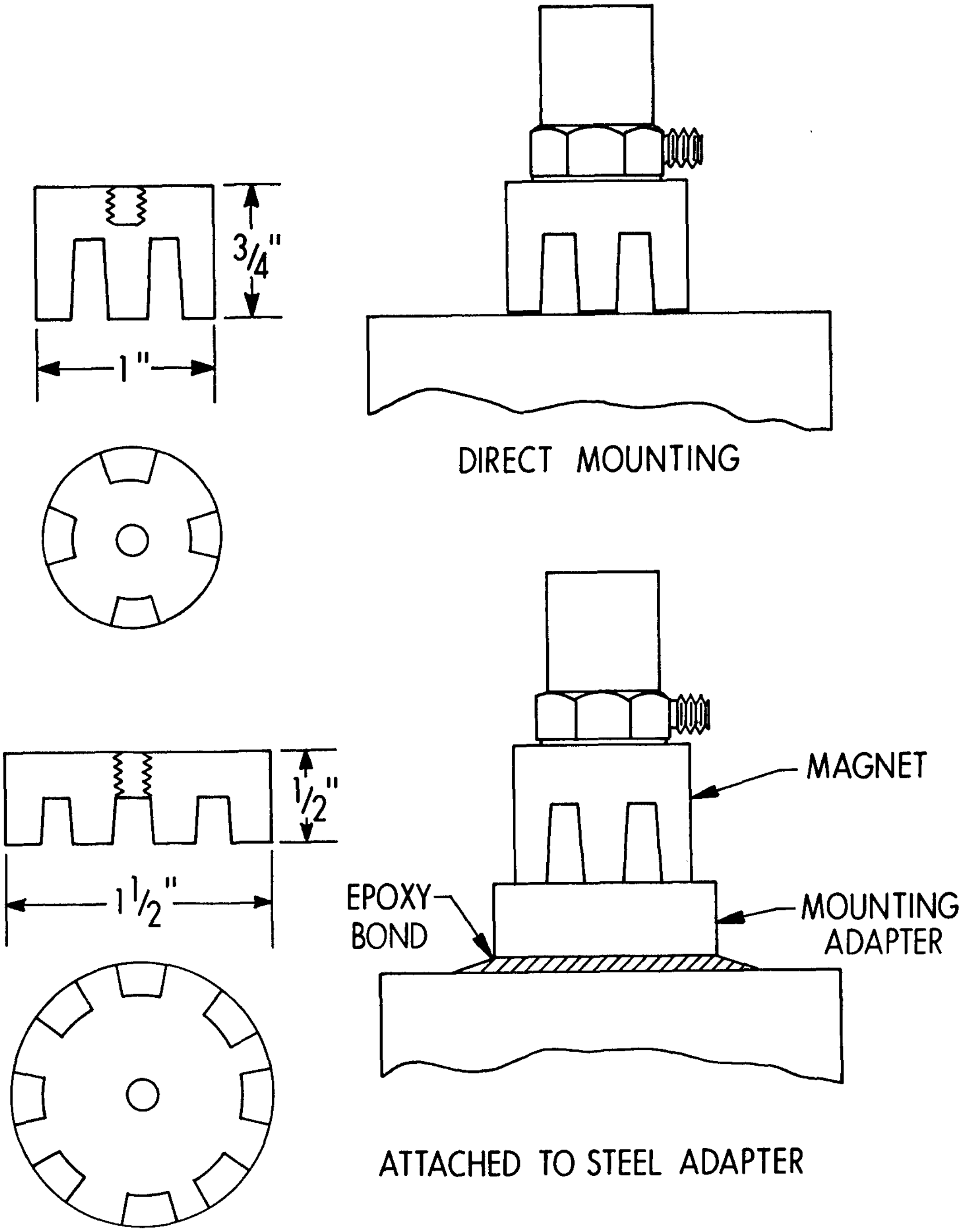


Figure 21
Magnetic Accelerometer Mounting Clamps

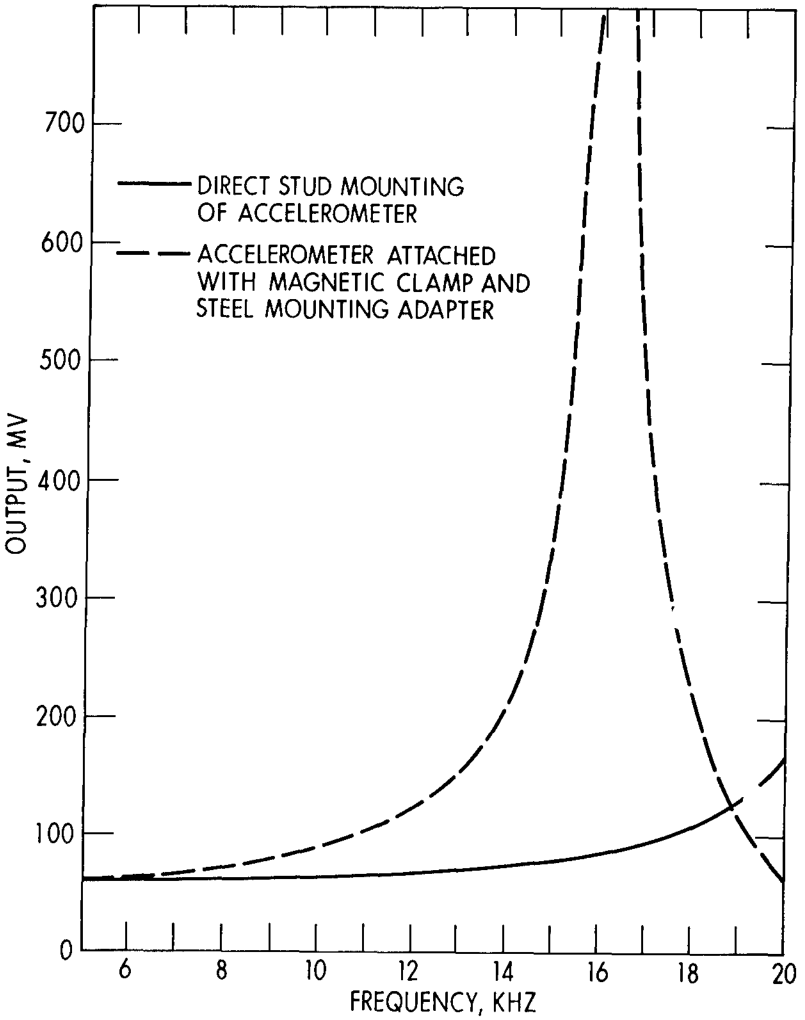


Figure 22
Effect of Magnetic Clamp Attachment
on Accelerometer Response

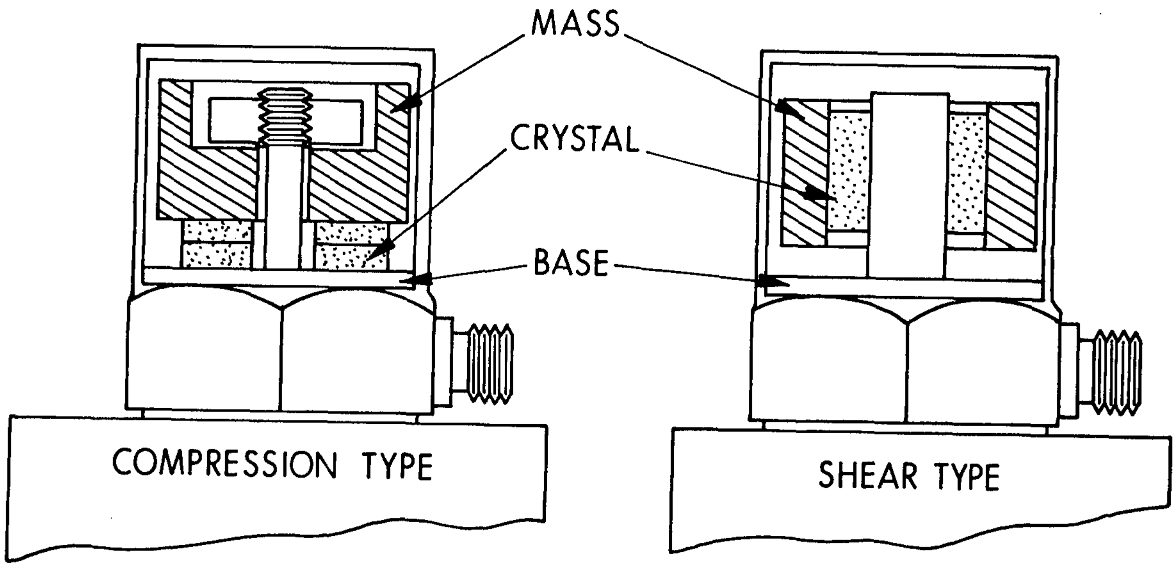


Figure 23
Compression- and Shear-Type Accelerometers

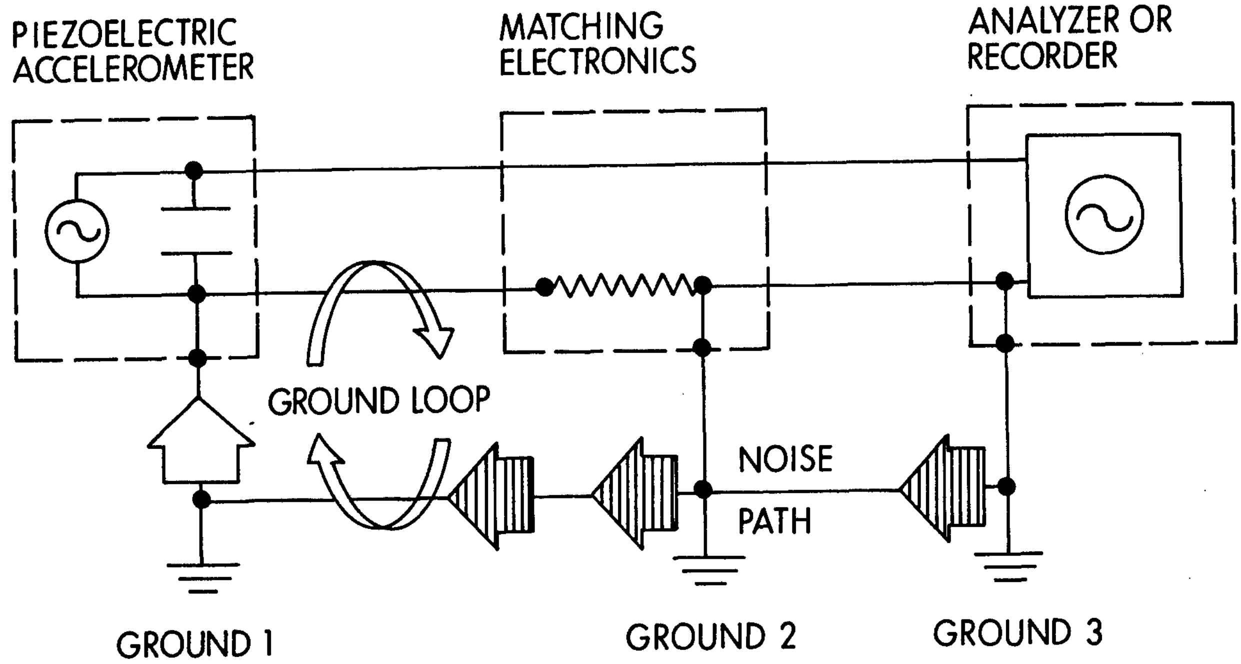


Figure 24
Current Coupling Equivalent Circuit

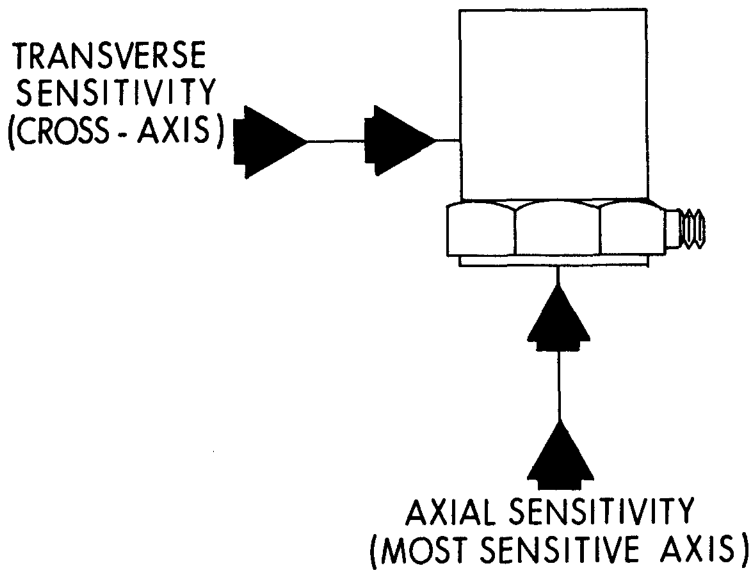


Figure 25
Accelerometer Transverse Sensitivity

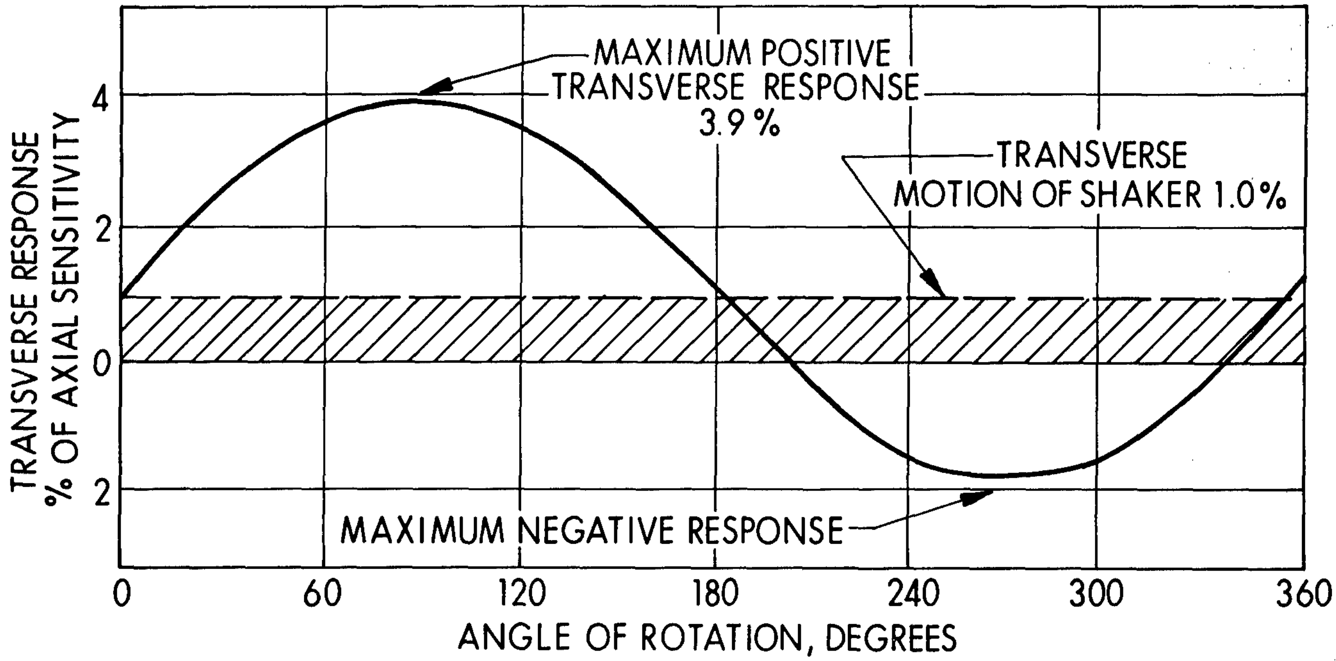


Figure 26
Transverse Response Versus Angle of Rotation

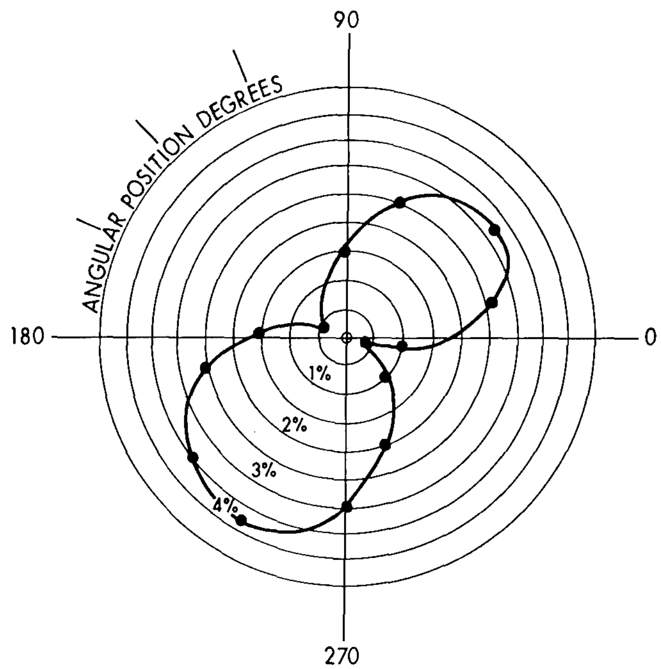


Figure 27
Polar-Coordinate Plot of Transverse Sensitivity

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13. ABSTRACT

After a brief review of the electromechanical functioning of the piezoelectric accelerometer, factors affecting its dynamic response characteristics and therefore the validity of vibration measurement are discussed. Consideration is given to variables such as shunt resistance and capacitance, mounting methods, base bending, cable noise, ground-loop currents, and environmental effects. Approved accelerometer mounting techniques that will ensure the accuracy and repeatability of the measurement are also described.

(Author)

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